INTRODUCTION TO ELECTRON CLOUD EFFECTS AND APPLICATION TO THE GSI PRESENT AND FUTURE MACHINES

Giovanni Rumolo (GSI-Darmstadt)

- Mechanisms of electron cloud formation

- Observation in existing machines and concerns for future machines

- Simulation of the build up process

- Single bunch instability driven by the electron cloud (mechanism and simulation)

- The e-cloud in the SIS18 and SIS100/300: thresholds for build up and instability

- Conclusions, some open questions and outlook

Historically....

- **Novosibirsk proton storage ring (1967):** unusual transverse instabilities occurred for bunched and unbunched beams. Model of coupled electron/beam centroid oscillation.

- **CERN ISR (1970s):**

  coasting beam instability and fast pressure rise for bunched proton beam

Later on in the 1980s....

- Los Alamos PSR (1988):

  fast instability with beam loss above a threshold current (for bunched and unbunched beams)

- KEK PF (1989):

  multibunch instability for positron bunch trains.

1990s up to nowadays !

- CERN 1997: a crash program is launched to study electron clouds.

- SPS and PS (since 1999): evidences for electron cloud with LHC type beams.

- KEKB and PEP-II (1999): e-cloud induced tune shifts along bunch train and instabilities.

- RHIC (2002): pressure rise, tune shift. Electron detectors installed. Background problem at PHOBOS probably caused by an electron cloud after rebucketing.

How an electron cloud builds up...

Primary electrons are produced via:

- residual gas ionization (like PS, SPS and most of hadron or ion machines)

$$\frac{d^2\lambda_e}{dsdt} \approx 2.5 \times 10^8 \, e^- m^{-1} s^{-1}$$

Ex. For SIS100/300 with a rest gas pressure of 4 x 10^{-3} nTorr

How an electron cloud builds up...

Primary electrons are produced via:

- Electron desorption from ion loss on the inner pipe wall (probably dominant in ion machines)

$$\frac{d^2 \lambda_e}{ds\,dt} \approx 2 \times 10^{13}\, e^- m^{-1} s^{-1}$$

Ex. For SIS100/300 having assumed an ion loss rate of 2% over 1s

How an electron cloud builds up...

Primary electrons are produced via:

- Photoemission from synchrotron radiation on the inner pipe wall (in positron machines and LHC)

$$\frac{d^2\lambda_e}{ds\,dt} \approx 6 \times 10^{18}\, e^- m^{-1} s^{-1}$$

Ex. For LHC in the arcs

But electrons can survive and multiply !!

- **True secondary electrons** caused by secondary emission at the pipe walls.

- **Elastically reflected electrons** (very likely at low energy incidence)

- **Re-diffused electrons** (precise modeling still needed)
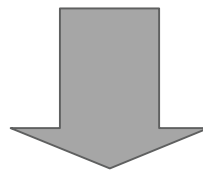
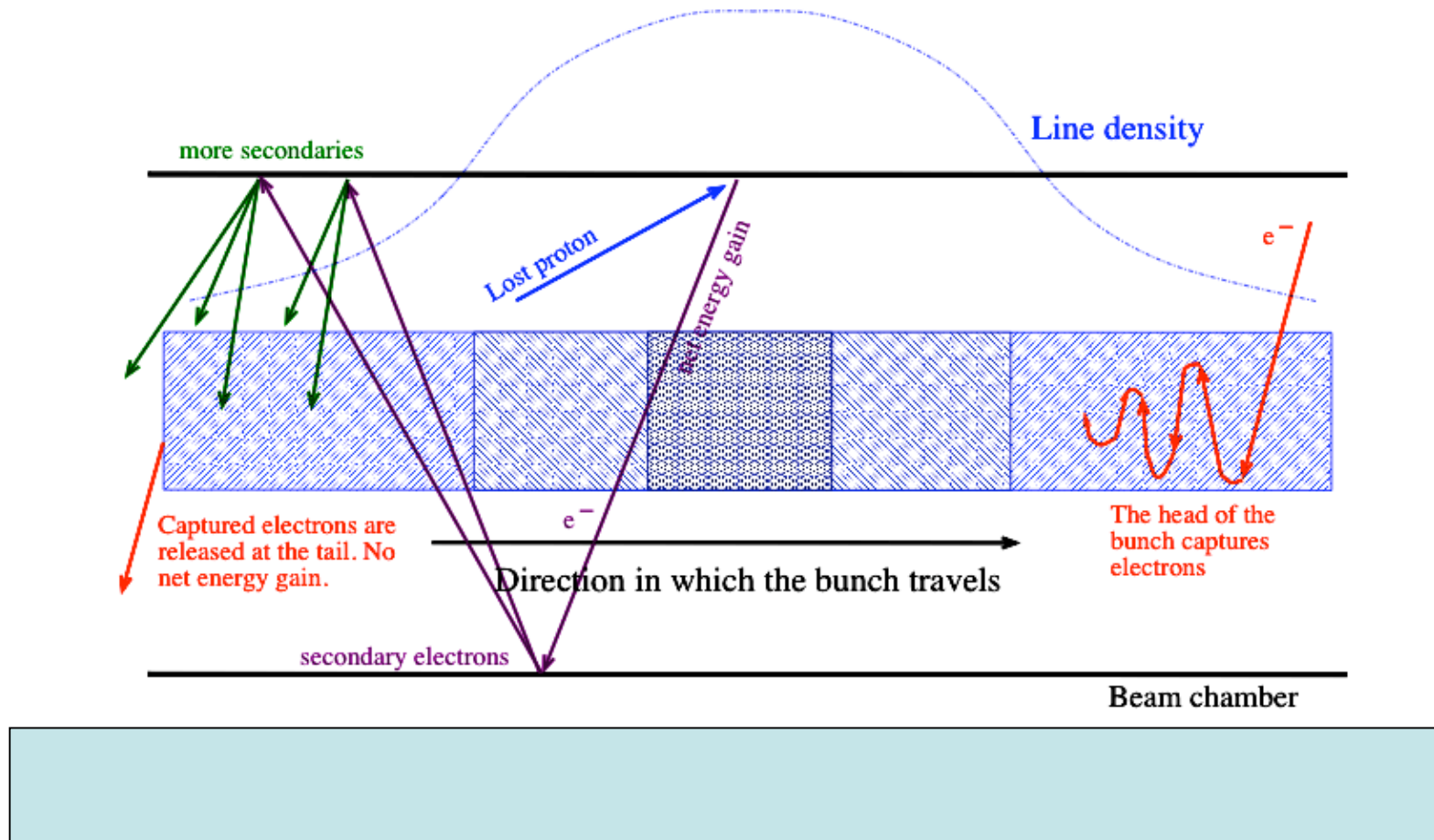**Exponential growth of the electron density inside the beam pipe !!!**

Schematic of electron cloud build up (1)

$$\frac{h_x^2}{N_b r_e L_{sep}} = 1$$
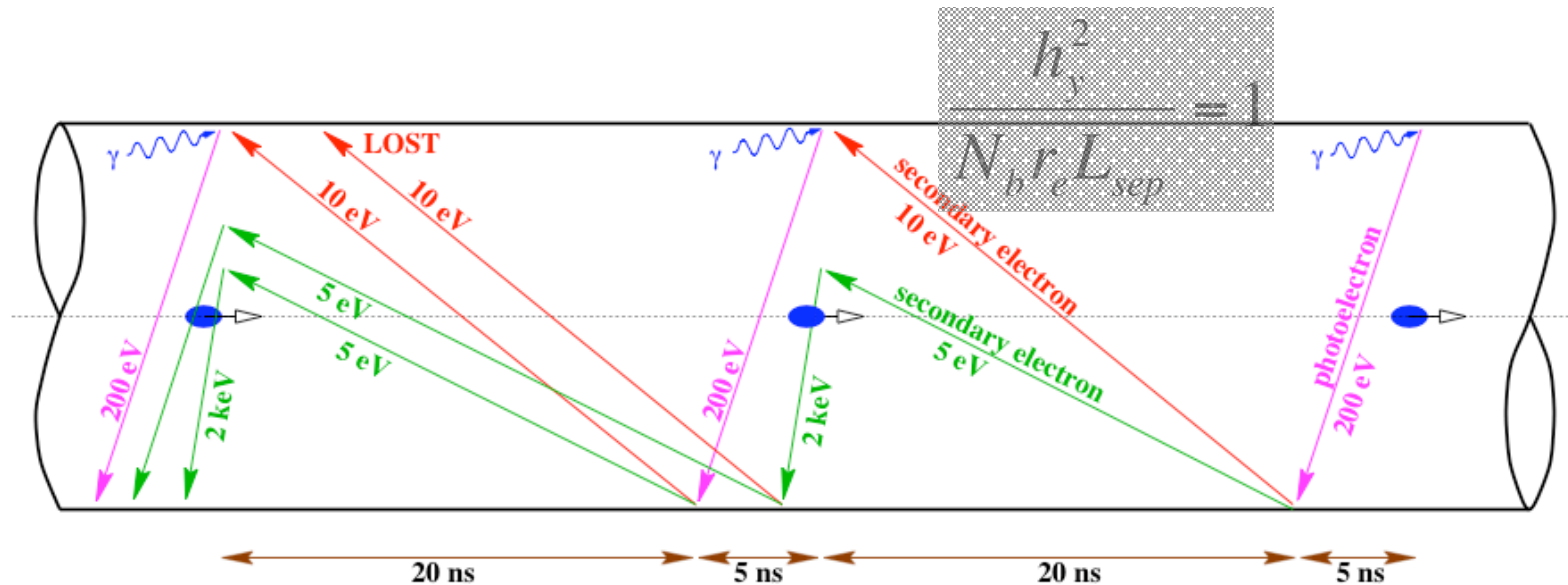
Principle of the multi-bunch multipacting. The resonance condition does not need to be exactly matched, wide ranges of parameters allow for the electron cloud formation

Schematic of electron cloud build up (2)

Principle of the trailing–edge multipacting

Line density

more secondaries

Lost proton

Fast energy gain

e⁻

Captured electrons are released at the tail. No net energy gain.

e⁻

The head of the bunch captures electrons

Direction in which the bunch travels

secondary electrons

Beam chamber

Electron cloud indicators

1. Nonlinear pressure rise
2. Spurious signal on the pick-up buttons
3. Signal on dedicated electron detectors and spectrum analysers
4. Tune shift along the bunch train
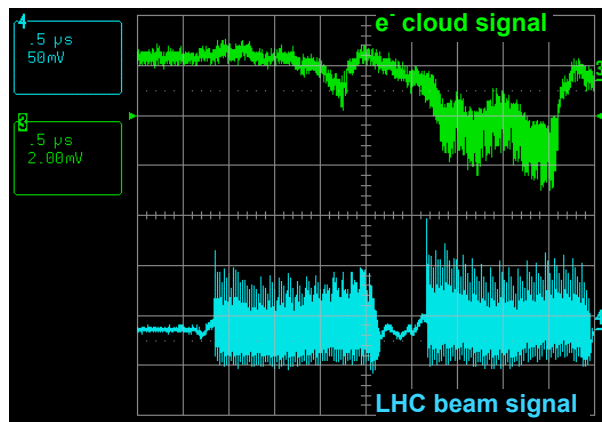5. Beam size blow-up and emittance growth
6. Luminosity drop in colliders

Observations at the SPS with LHC-type beams (1)
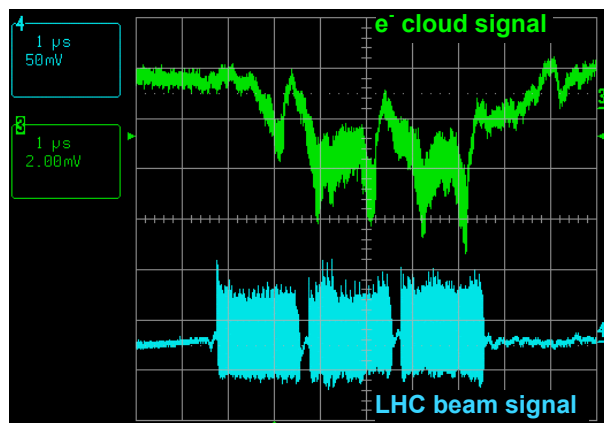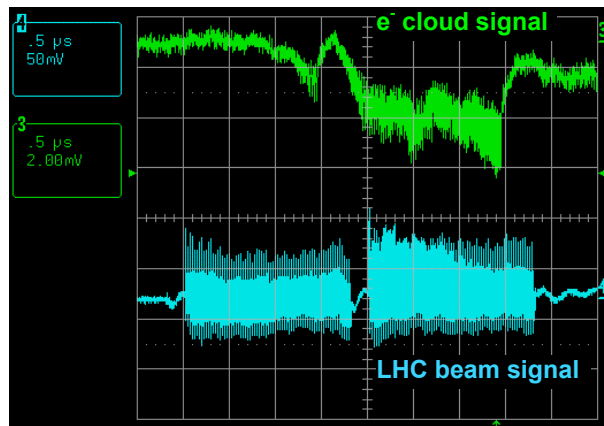
Two or three bunch trains (72 bunches) are injected into the SPS with 8 gaps inbetween. The pick-up electrodes reveal the electron cloud signal
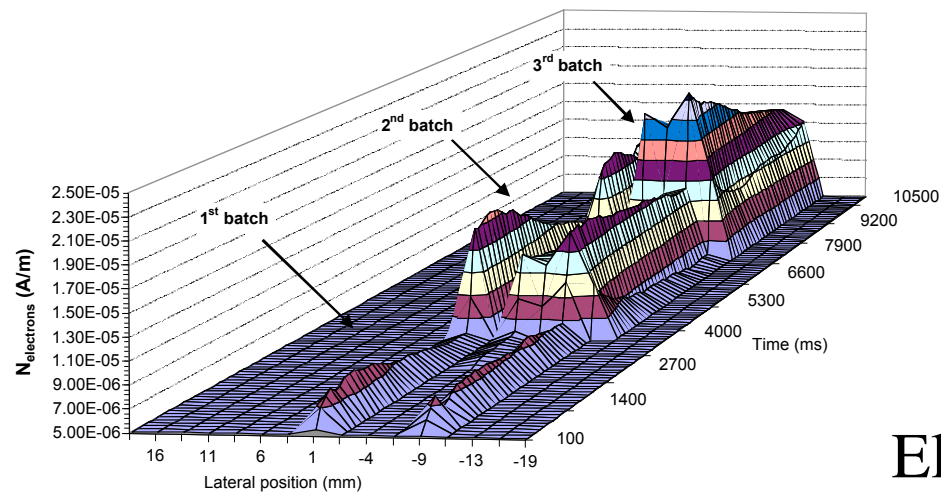
Observations at the SPS with LHC-type beams (2)

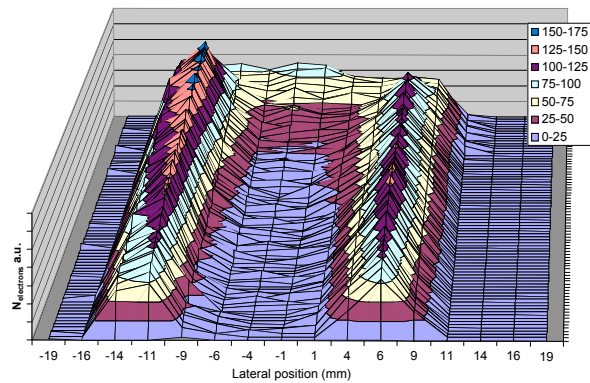e⁻ cloud signal

LHC beam signal

e⁻ cloud signal

LHC beam signal
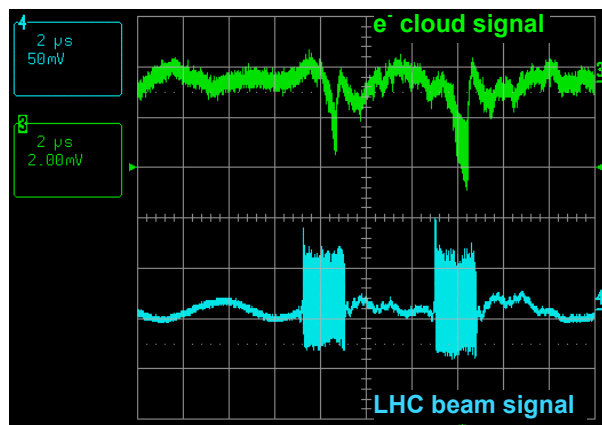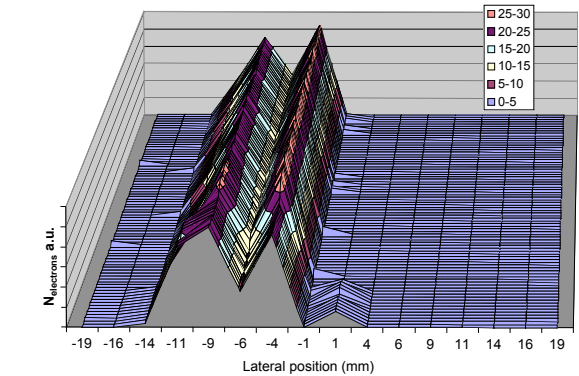
Two bunch trains are injected into the SPS with larger gaps inbetween. The pick-up electrodes still reveal a quickly growing electron cloud signal after the first train, due to a long memory effect.

Observations at the SPS with LHC-type beams (3)

Electron cloud activity measured using the strip-detector with a multi-batch injection in a dipole field.

Observations at the SPS with LHC-type beams (4)

N_electrons a.u.

Lateral position (mm)

Legend: 25-30, 20-25, 15-20, 10-15, 5-10, 0-5

N_electrons a.u.

Lateral position (mm)

Legend: 150-175, 125-150, 100-125, 75-100, 50-75, 25-50, 0-25

The strip-detector shows the two stripes in the electron distribution inside a dipole field region. The position of the stripes depends on the bunch intensity and on the field strength.

Beam axis

Pumping holes in the beam screen

2001   2002

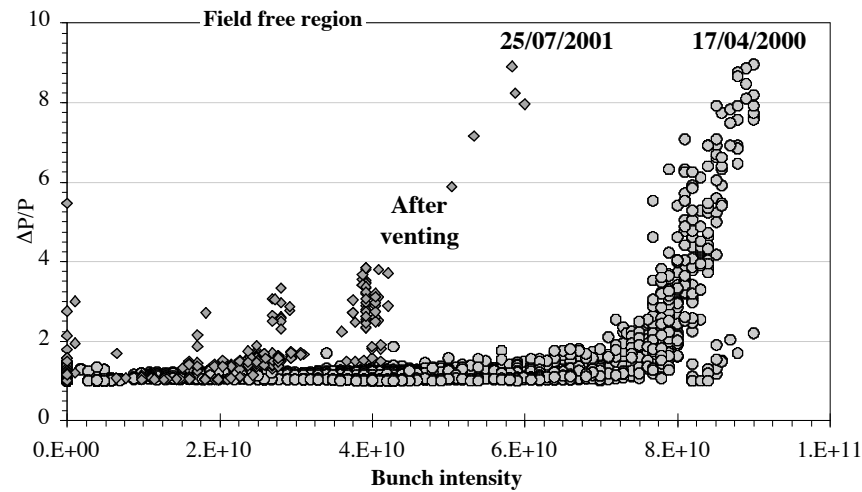Bunch intensity (p/bunch)
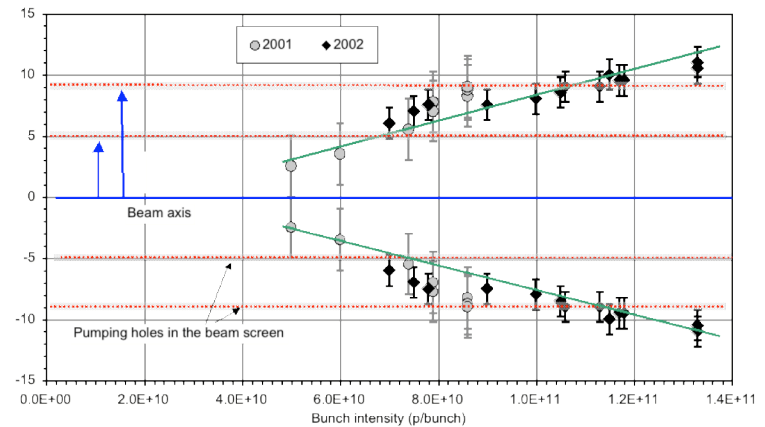
Observations at the SPS with LHC-type beams (5)
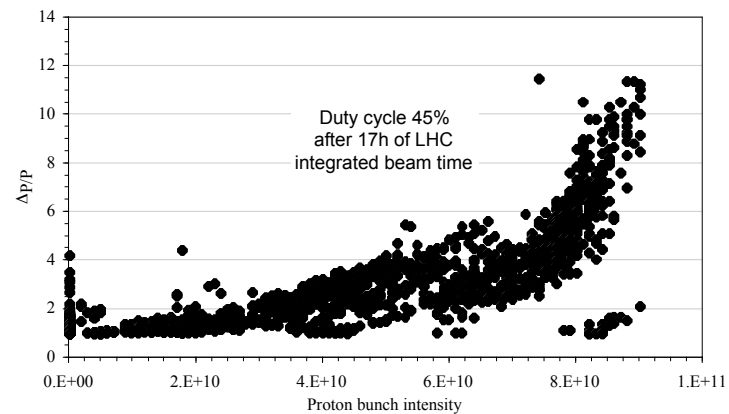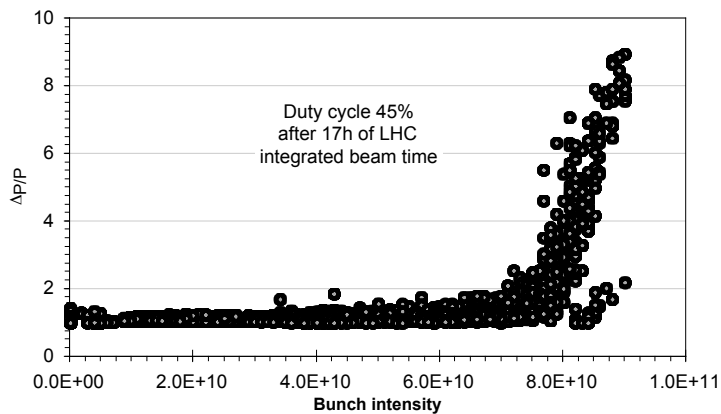
Electron induced pressure rise versus proton bunch intensity in a field free (left) and dipole (right) region. Static pressure was 10^{-6} Pa.
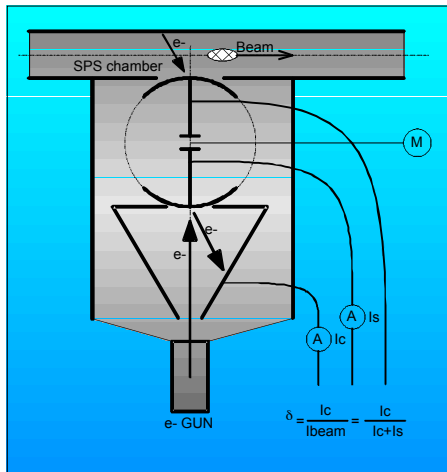
Example of scrubbing
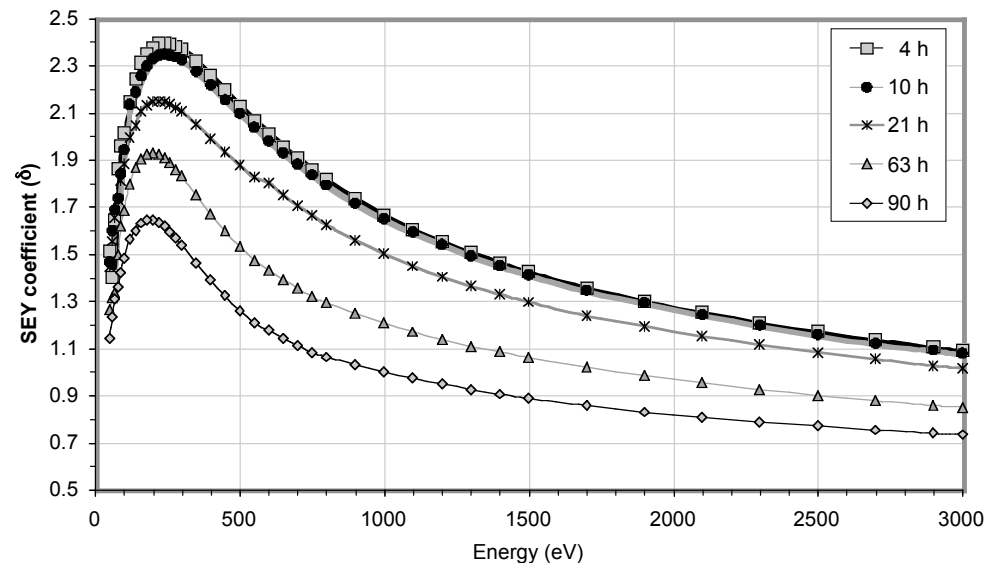
Observations at the SPS with LHC-type beams (6)

Electron induced pressure rise. Thresholds of the electron cloud in 2000 and in 2001 after a long venting to atmosphere of the SPS machine.

Observations at the SPS with LHC-type beams (7)

Schematic view of the in-situ SEY
detector installed in the SPS

Scrubbing effect: decrease of the SEY of a copper
sample exposed to the bombardment of the electrons
from the cloud in the SPS as a function of the LHC
beam time.

Go to KEK instability

Observations at the KEKB LER

- Vertical beam size blow up along the bunch train

- Tune shift along the bunch train

- Solenoids can suppress or mitigate those effects.

- Operation with high positive chromaticity helps against the beam instability

- Luminosity is seriously affected by these phenomena and e-cloud is presently still an issue for the near-future luminosity upgrade...

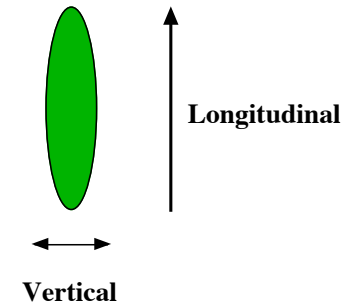# *Observations at the KEKB LER*
a few pictures... [courtesy K. Ohmi]
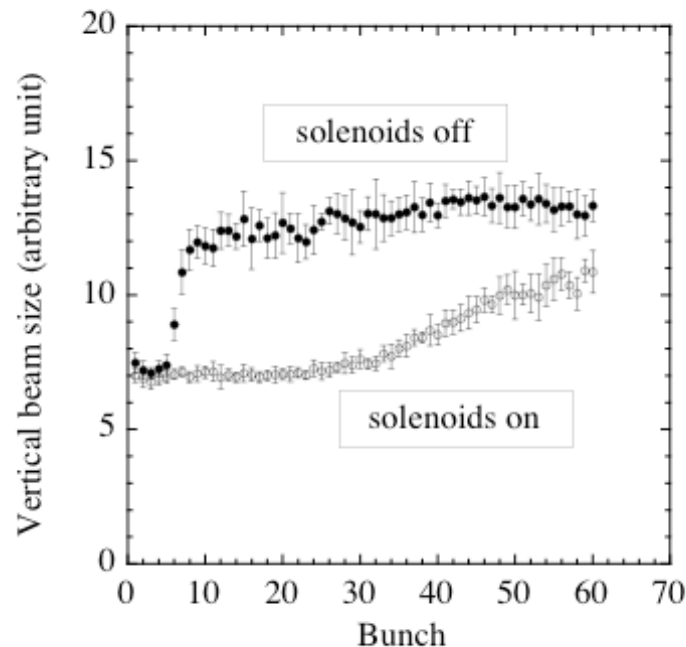
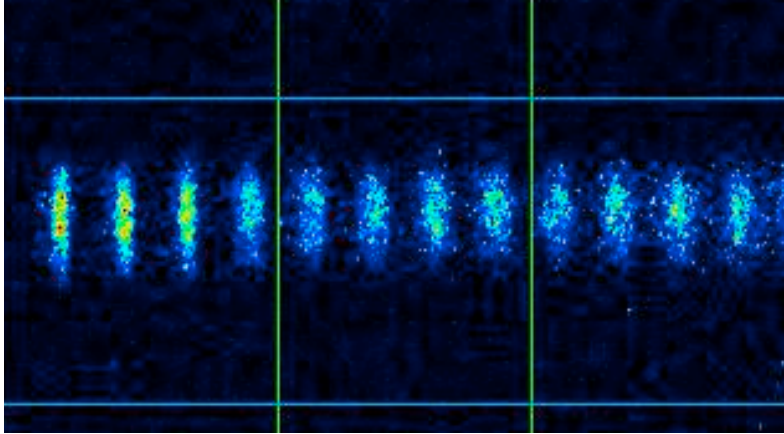Example of beam size blow up along a bunch train,
with and without the solenoids.

Observations at the KEKB LER
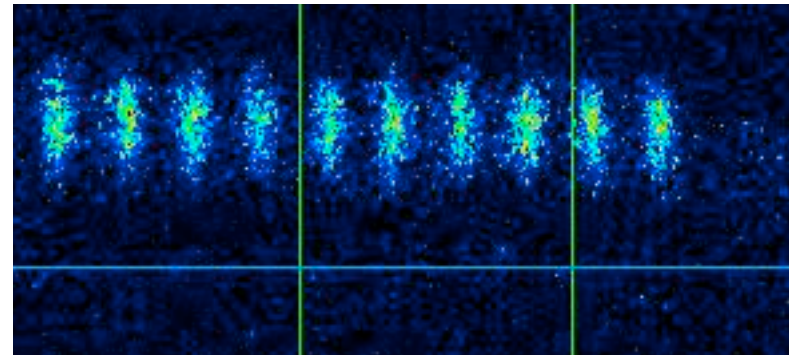## *a few pictures... [courtesy K. Ohmi]*

Vertical beam size blow up observed
with a streak camera (900 mA)

Longitudinal

Vertical

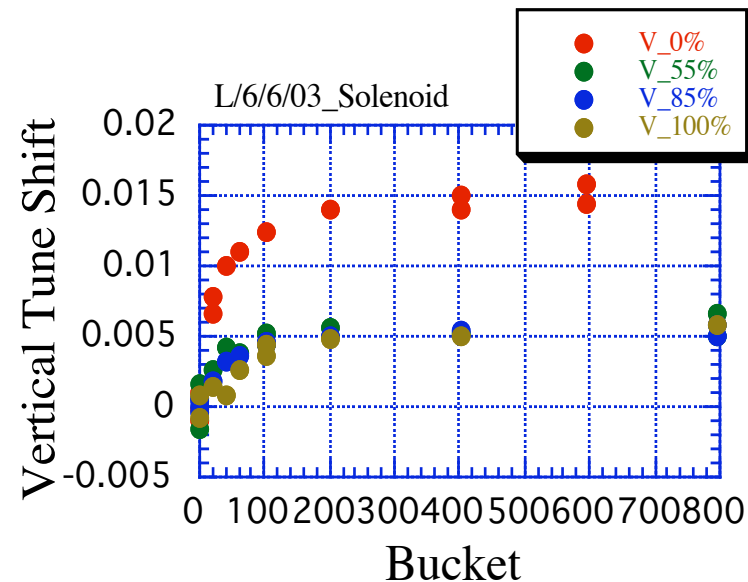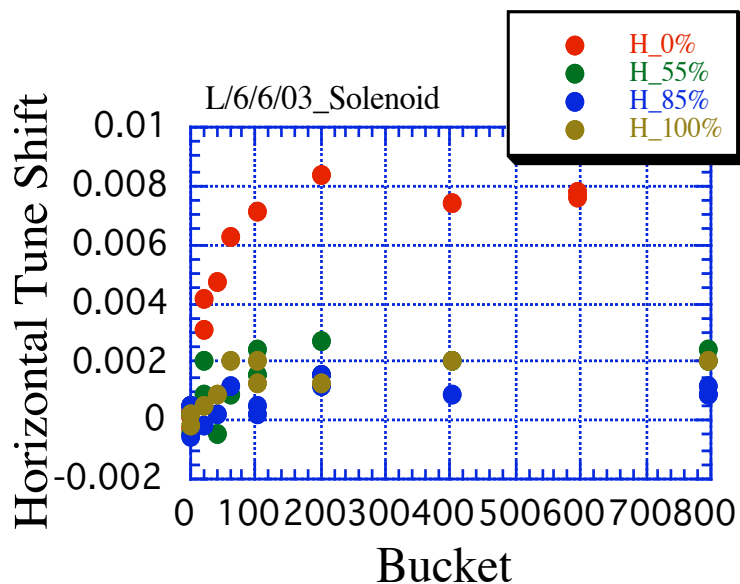**Train head**

Train tail

The vertical beam size starts increasing after the 3rd bunch. No
clear head tail motion is visible.

Observations at the KEKB LER
a few pictures... [courtesy K. Ohmi]

Tune shift from the e-cloud: $\Delta \nu_{x,y} = \dfrac{r_e}{2\gamma} \cdot \oint \rho \cdot \beta_{x,y} \cdot ds$
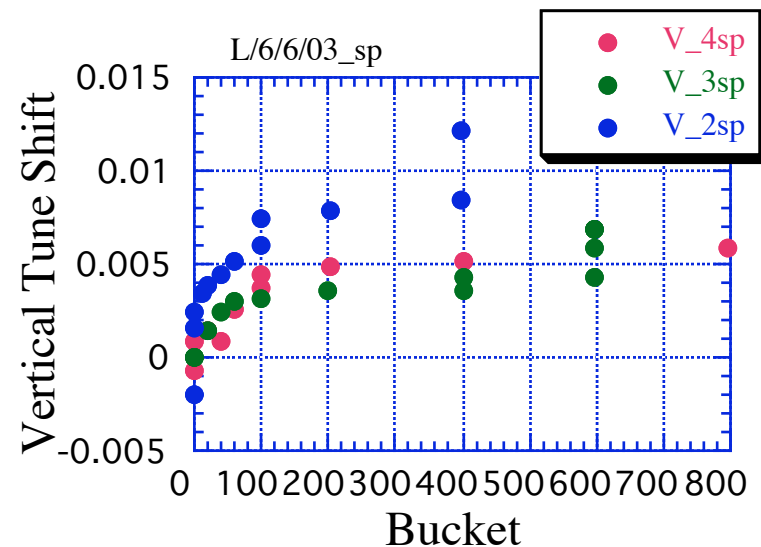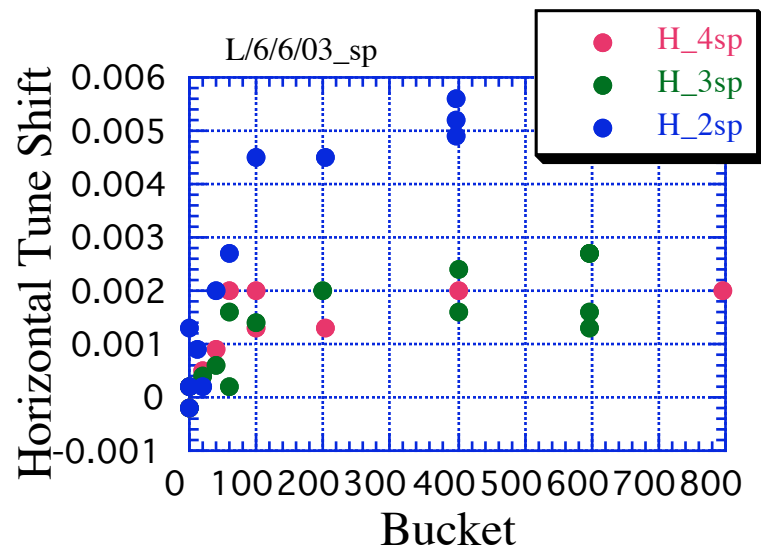

4 trains, 200 bunches/train, 4 bucket spacing, bunch current 0.58mA, different values of the solenoidal field.

Observations at the KEKB LER
a few pictures... [courtesy K. Ohmi]
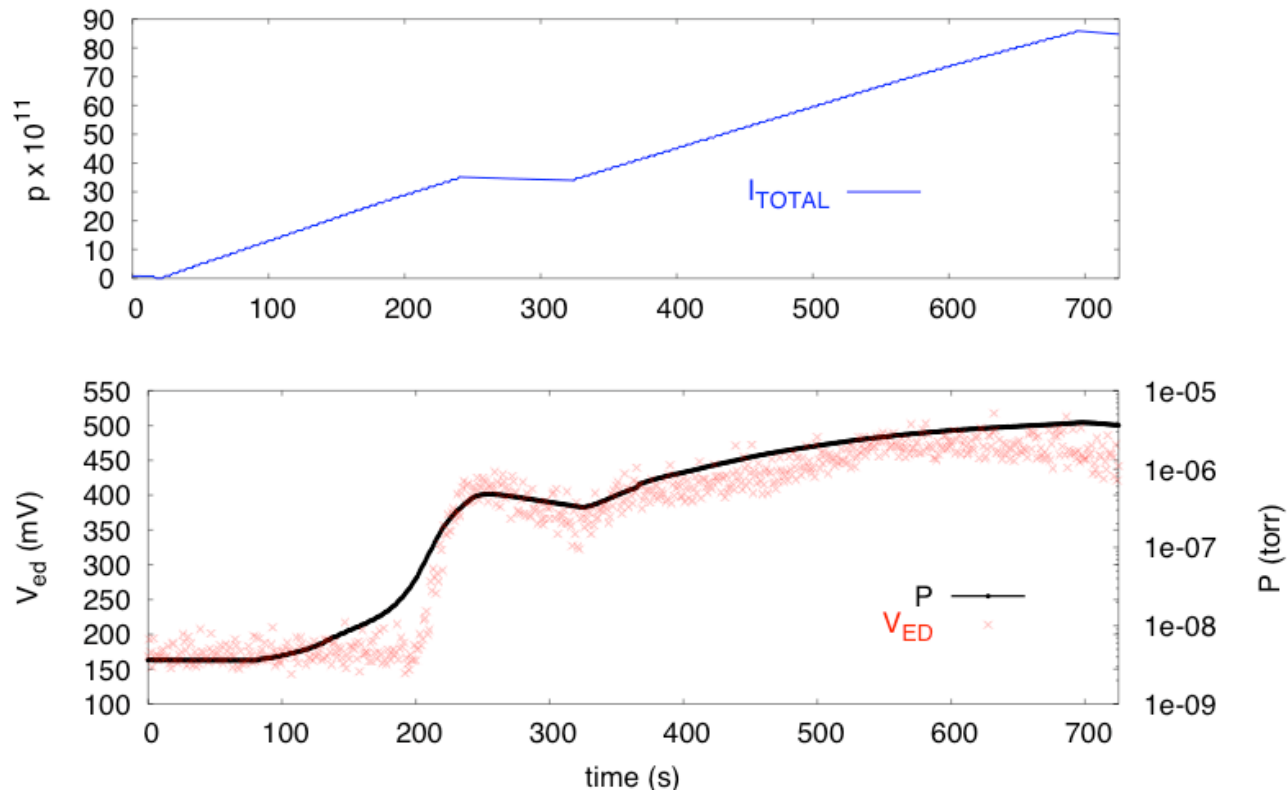
Tune shift from the e-cloud:

4 trains, 200 bunches/train, 4 bucket spacing, bunch current
0.58mA, different types of bunch spacing.
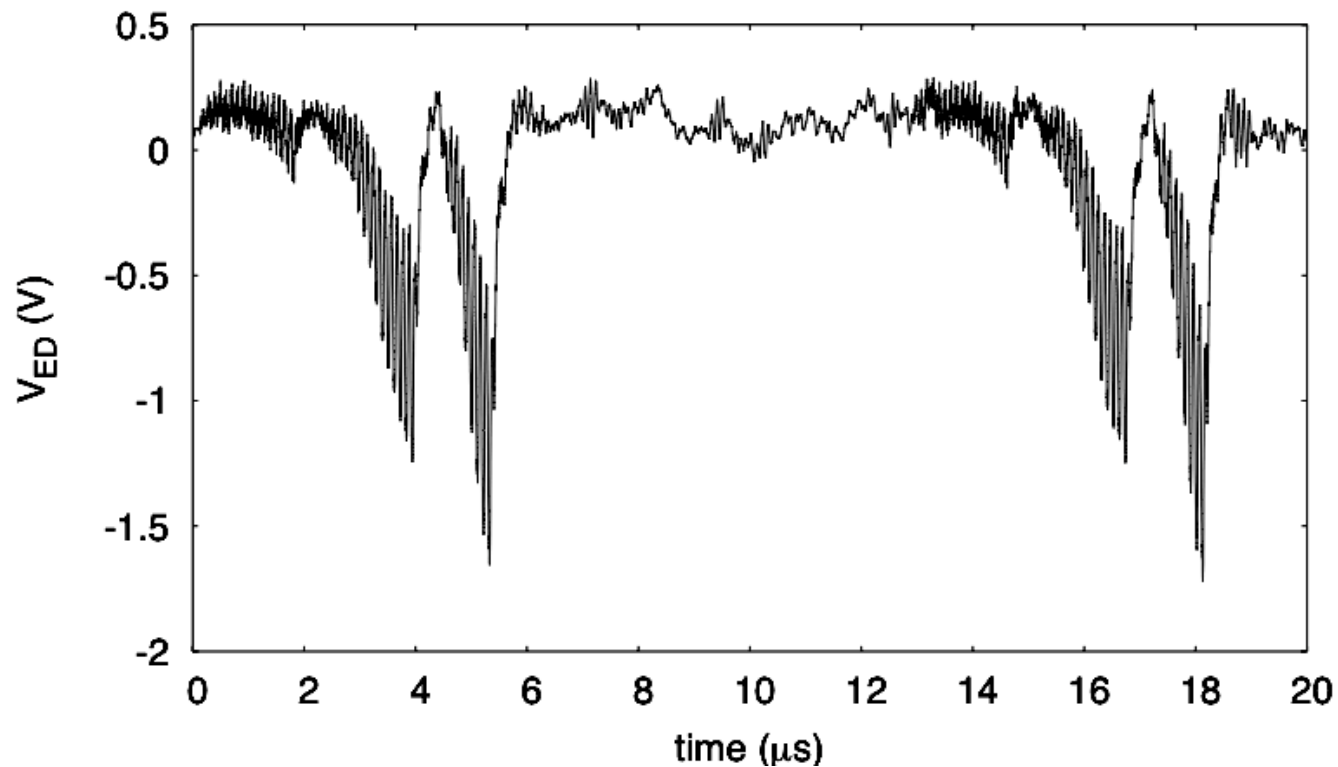
Future machines

Observations at RHIC
[courtesy U. Iriso]

Injection of 110 bunches into RHIC (temporarily stopped after 45 bunches). Pressure rise and signal from an electron detector.
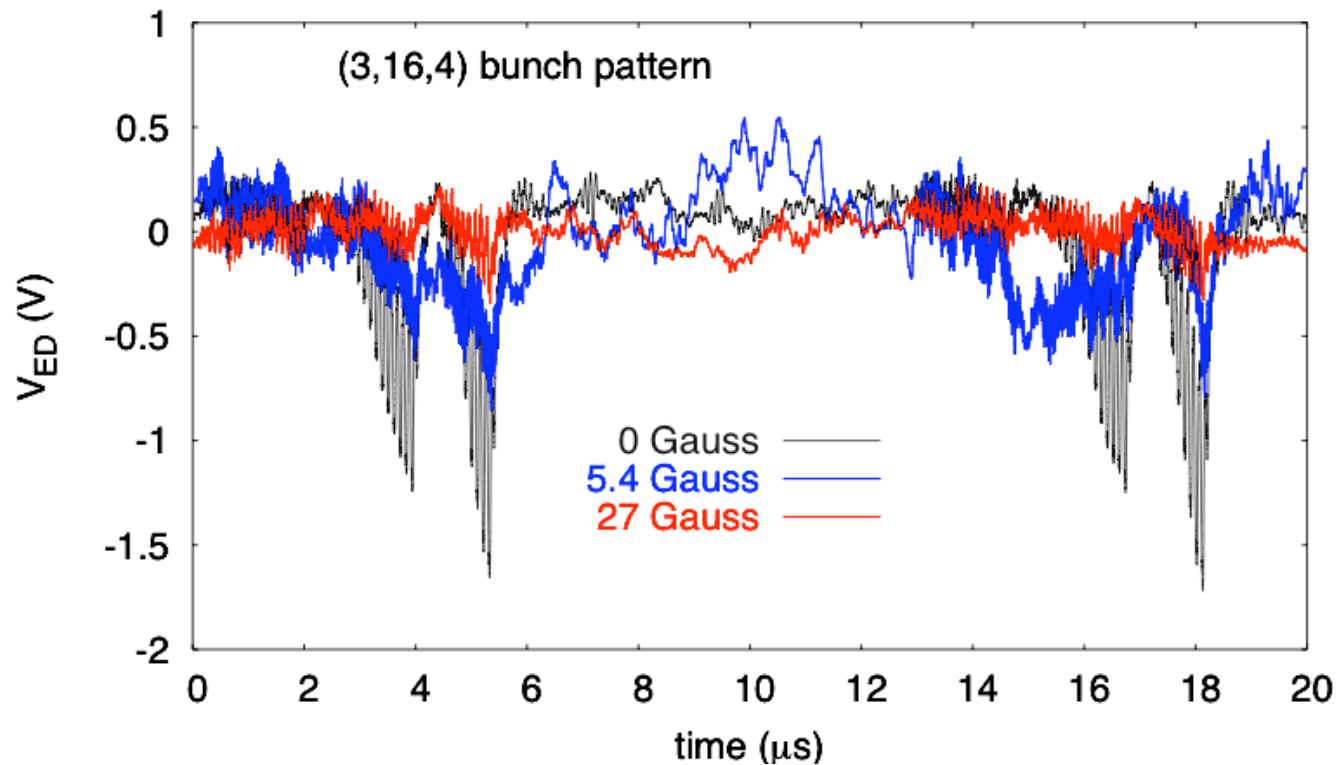
Observations at RHIC [courtesy U. Iriso]

Signal from the electron detector -without solenoidal field- with a (16 bunches, 4 ghost bunches) pattern.

Observations at RHIC [courtesy U. Iriso]
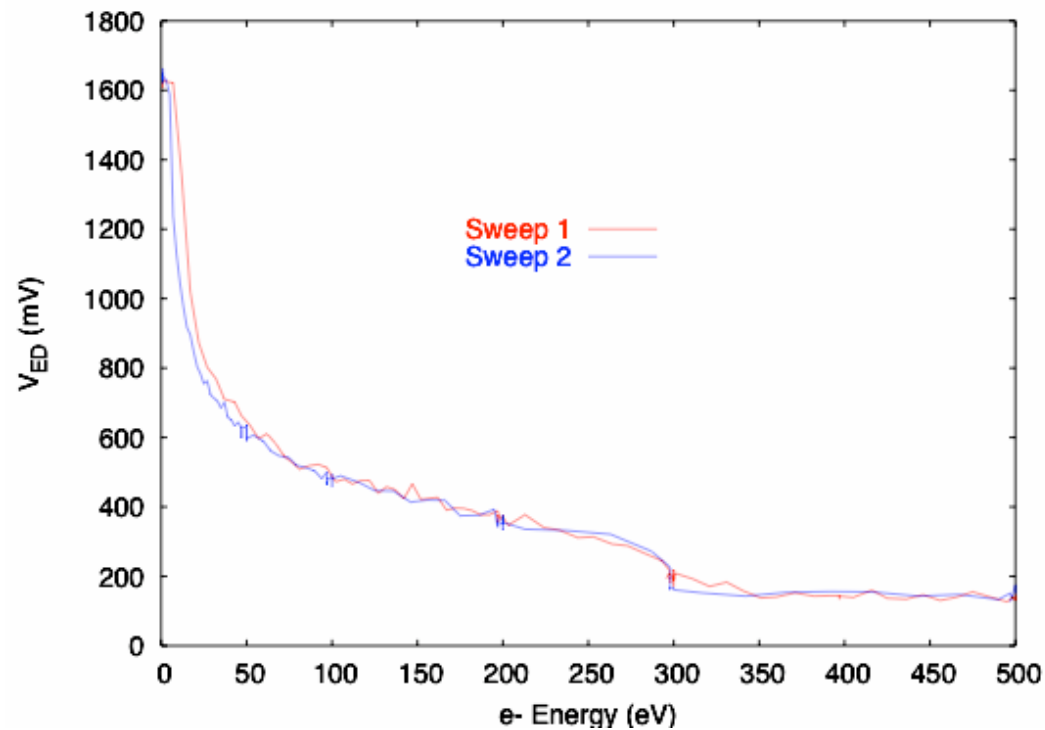

Signal from the electron detector, with and without solenoidal field, with the same bunch pattern as before.

Observations at RHIC [courtesy U. Iriso]

Example of measured energy spectrum of the electrons (data acquired after injection of 45 bunches)

Concerns for future machines

- Degradation of the vacuum (background at the IP's in colliders, pressure runaway in ion rings)
- High heat load in the dipoles (which can exceed the cooling capacity of the cooling system) for superconducting rings.
- Emittance growth and beam quality degradation
- Single and coupled-bunch instability and beam loss
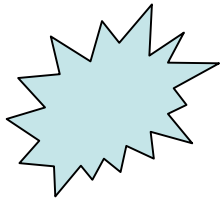
Reliable simulation tools and extensive simulation campaigns are needed !!!

# Two types of simulations

- **Electron cloud build up simulations**: the process of e-cloud formation is simulated inside the section of an accelerator vacuum chamber.

- **Instability simulations**: the electron cloud is assumed pre-existing and its effects on the beam are simulated.

- Recent integration of the two functions into one single code (for coasting beams)

Two types of simulations (II)

- Electron cloud build up codes:
    - ECLOUD (*CERN-GSI-RAL*, Zimmermann, Rumolo, Bellodi, Brüning, Schulte)
    - POSINST (*LBNL-SLAC*, Furman, Pivi)
    - COUNTRY-CLOUD (*BNL*, Wang)
    - CSEC (BNL, Blaskiewicz)
    - PEI (*KEK*, Ohmi)
- Instability simulation codes:
    - HEADTAIL (*CERN-GSI*, Rumolo, Benedetto)
    - QuickPIC (*USC-GSI*, Katsouleas, Ghalam, Rumolo)
    - PEHTS (*KEK*, Ohmi)

Build up code simulation recipe (ECLOUD)

Beam pipe
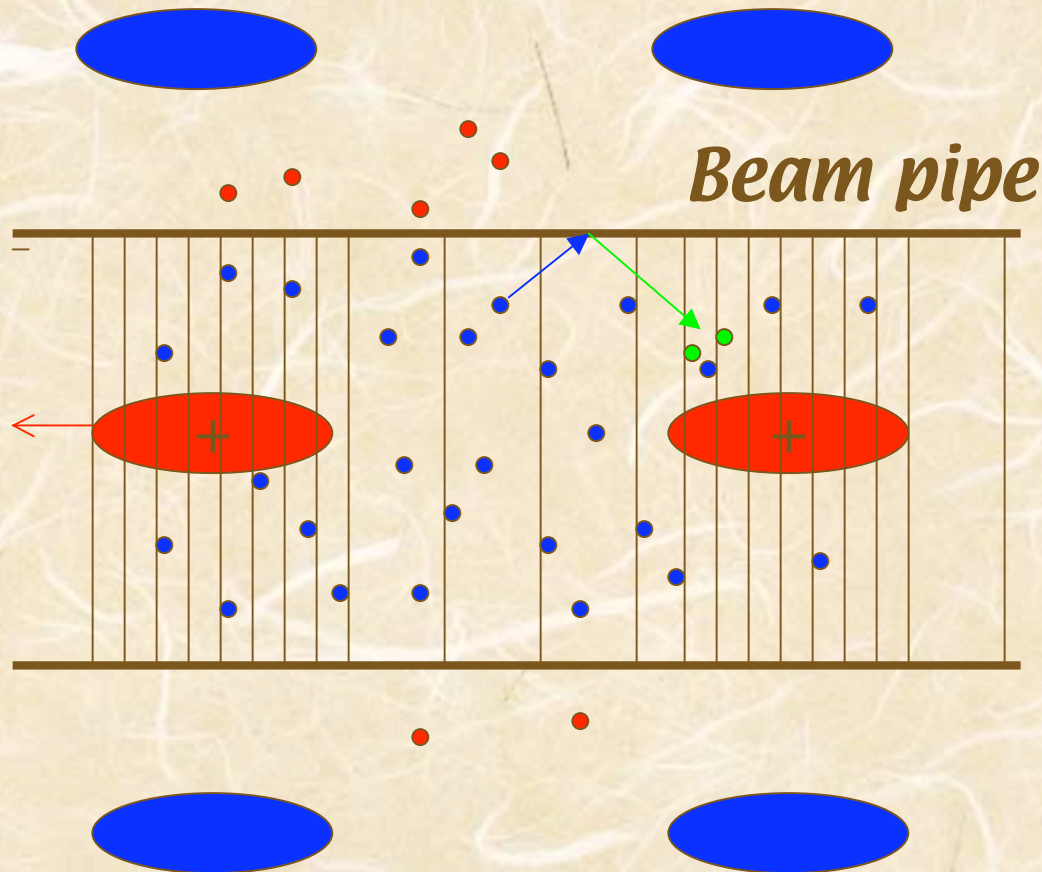
- focus on a beam line section (1m for ex.)

- slice bunch and interbunch gaps

- represent e- by macroparticles: create and accelerate e- in beam and image fields

- if the e- hits the wall create secondaries by changing its charge.

ECLOUD features

- **Multi-bunch** passage, dipole/field-free/solenoid sections
- 3D electron kinematics
- Transverse electron space charge effects
- Transverse beam-electron forces
- Circular/elliptical/rectangular chamber
- Perfectly conducting walls

Necessary laboratory inputs for ECLOUD

- **Photoelectric/ionization/proton loss efficiency** in terms of electron production
- **Energy spectra** and **angular distributions** of primary electrons
- **Secondary emission process**: probability of secondary emission, elastic reflection or rediffusion.
- ? **Energy distribution** of the secondary electrons.

Reflected and secondary e⁻'s

Recent measurements (Cimino-Collins) indicate that in
the low energy range elastic reflection becomes dominant.
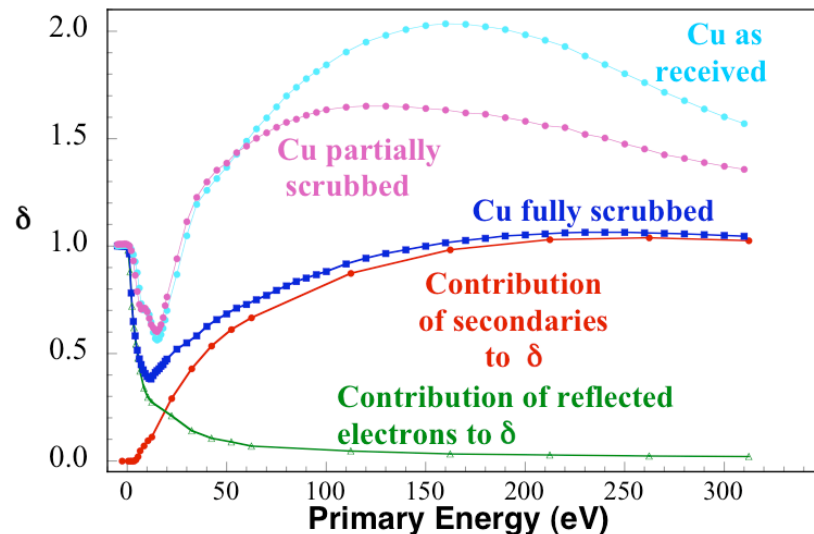
The probability of elastic reflection converges to 1 for vanishing energy of the
incident electron (submitted to **PRL** - Cimino, Collins, Furman, Ruggiero,
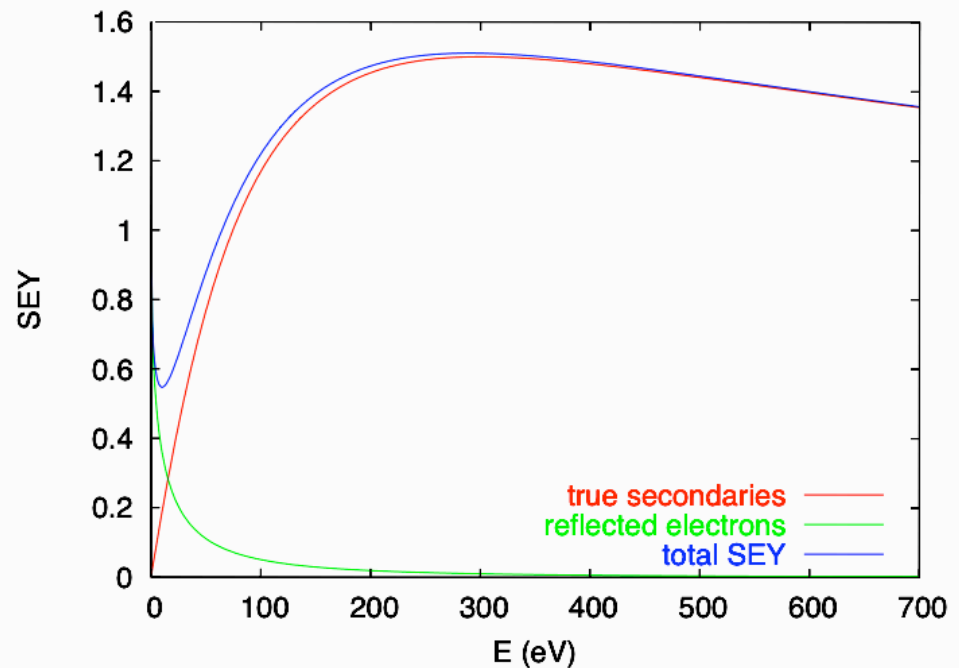Rumolo, Zimmermann)

In the code we use the following parametrizations:

$$\delta_{true}(E) = \delta_{max} \frac{s(E/E_{max})}{[s - 1 + (E/E_{max})^s]}$$

$$\delta_{tot}(E) = \delta_{true}(E) + \delta_{elas}(E)$$

$$\delta_{elas}(E) = \frac{(\sqrt{E} - \sqrt{E + E_0})^2}{(\sqrt{E} + \sqrt{E + E_0})^2}$$

Rediffused electrons are not accounted for in this parametrization !

Single bunch instability

- ✓ Electrons are accumulated around the beam center during the bunch passage (pinch)
- ✓ If there is a displacement between head and tail, the tail feels a net „wake" force
- ✓ Effective short-range wake field -- TMCI type of instability.
- ✓ Causes head-tail motion and emittance growth
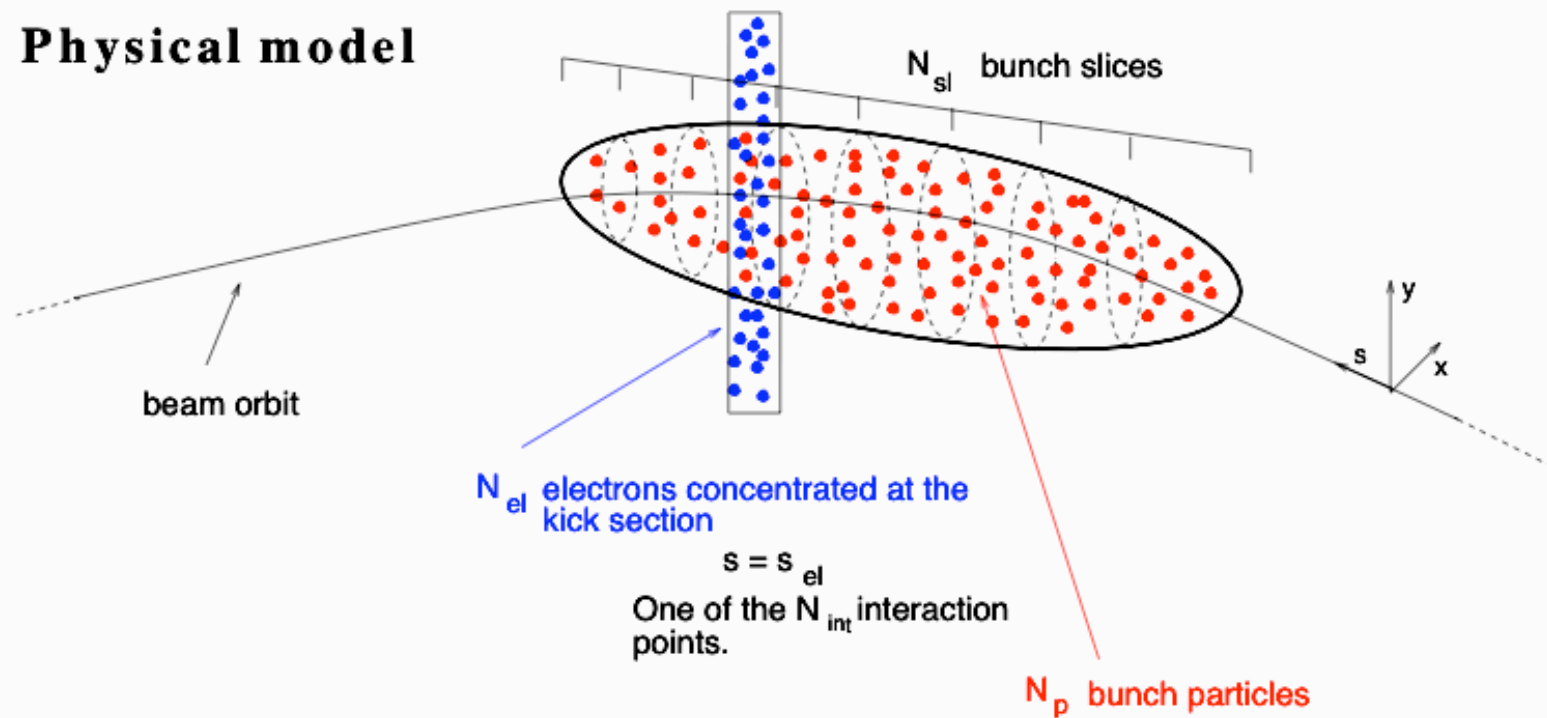- ✓ Observed at CERN PS and SPS, KEKB LER, and PEP II.

Electron cloud instabilities (approaches)

- **Coupled bunch instability** (KEK Photon Factory SR 1995, horizontal at SPS 2000)

- 2-particle model with length (Ohmi & Zimmermann, 2000)

- Broad-band approximation of the e-cloud wake field (Ohmi et al., 2000)

- Various simulation codes: microbunches, soft Gaussian, PIC (Rumolo, Ohmi, 2001)

- 3- and 4-particle models including space charge and beam-beam (Rumolo, Zimmermann, 2001)
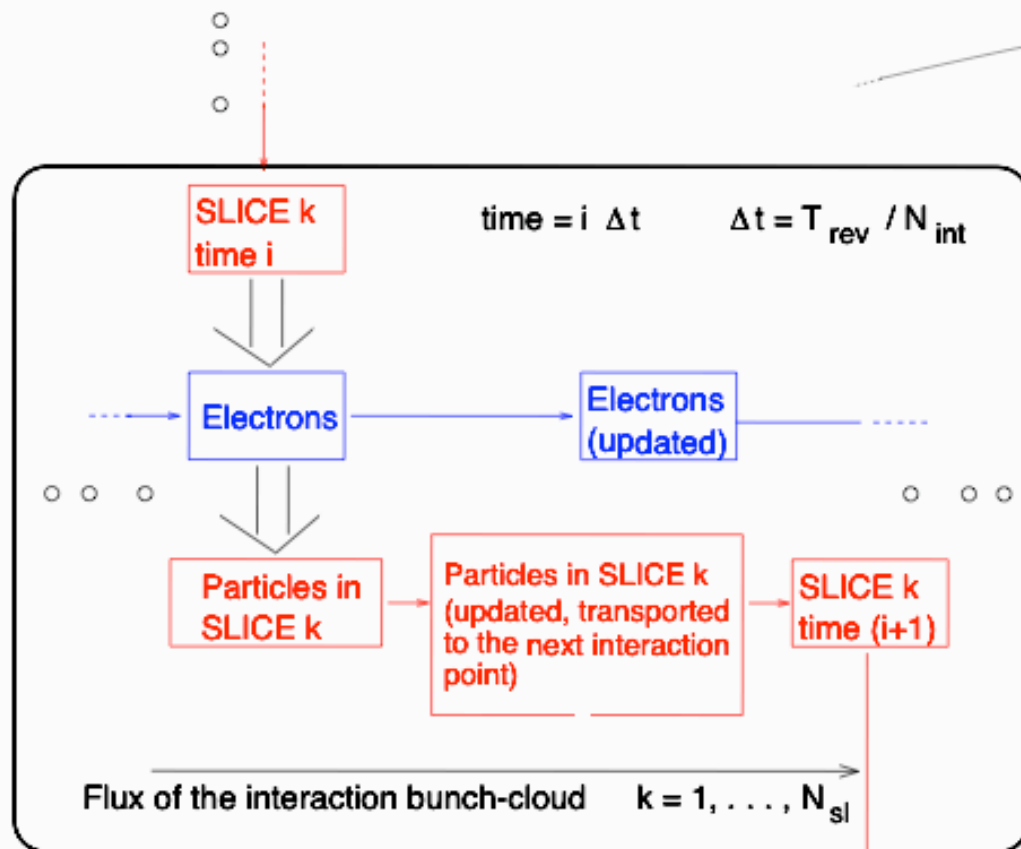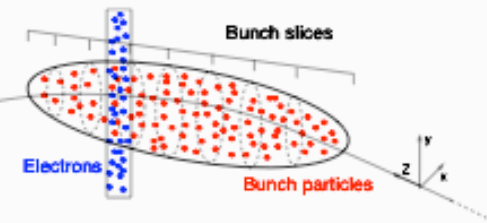
Single bunch type

Code HEADTAIL

Physical model

N_{sl} bunch slices

beam orbit

N_{el} electrons concentrated at the kick section

$s = s_{el}$
One of the N_{int} interaction points.

N_p bunch particles

Simulation model: electron cloud and bunch are both modelled as ensembles of macro–particles (typically 100000) and the bunch is divided into an adjustable number of slices (typically 50).

Numerical implementation

Physical model

SLICE k
time i

$time = i \, \Delta t$ $\Delta t = T_{rev} / N_{int}$

Electrons

Electrons (updated)

Particles in SLICE k

Particles in SLICE k (updated, transported to the next interaction point)

SLICE k time (i+1)

Flux of the interaction bunch-cloud $k = 1, \dots, N_{sl}$

Time flux

$i = 0, \dots, N_{turn} \times N_{int} - 1$

Features of HEADTAIL (I)

- Synchrotron motion can optionally be taken into account
- Single bunch can be Gaussian or uniform (superbunch). Longitudinal dynamics is solved in a linear, sinusoidal or no bucket.
- Chromaticity rotation and detuning with amplitude
- Electron cloud kick(s):
  - Soft Gaussian approach (finite size electrons)
  - PIC module (with or without conducting boundaries)
  - Uniform or 1-2 stripes initial e-distributions

Features of HEADTAIL (II)

- Short range wake field due to a broad band impedance

$$Z_{1\perp}(\omega) = \frac{\omega_R}{\omega} \frac{Z_\perp}{1 + iQ_\perp \left(\dfrac{\omega_R}{\omega} - \dfrac{\omega}{\omega_R} \right)}$$

- Space charge: each bunch particle receives transversely a kick proportional to the local bunch density around the local centroid. Longitudinal optional.

- Linear coupling between transverse planes

$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix} = M_1(\delta p) M_2(I_x, I_y) \left[M_{sc}(z) \begin{pmatrix} x_n - \hat{x}(z) \\ x'_n + \Delta x'_{EC, Z_{1\perp}} - \hat{x}'(z) \end{pmatrix} + \begin{pmatrix} \hat{x}(z) \\ \hat{x}'(z) \end{pmatrix} \right]$$

Features of HEADTAIL (III)

- ~~Number and charge of macro-electrons fixed.~~

- Electron dynamics is resolved transversely in the nonlinear beam field and in optional configurations of magnetic field (field-free, dipole, solenoid, combined function)

$$\ddot{\overline{r}}_e - \frac{e}{m_e}\left(\overline{E}(\overline{r}_e) + \dot{\overline{r}}_e \times \overline{B}_{ext}\right) = 0$$

- ~~Electrons elastically reflected at the walls.~~
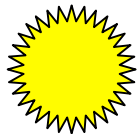
  NEW: for coasting beams, electrons are generated turn by turn according to the ionization or proton/ion loss rate, and can generate secondaries by impact with the pipe wall (charge of the macro-electrons is changed)
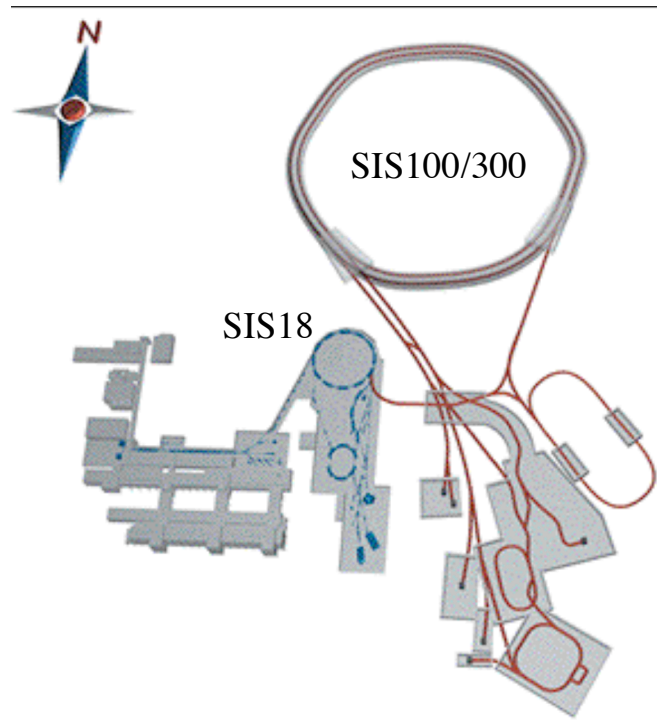
Electron cloud simulations for the SIS18 and SIS100/300

- Thesholds for build-up and instability
- Parametric study
- Could the electron cloud be a concern ?
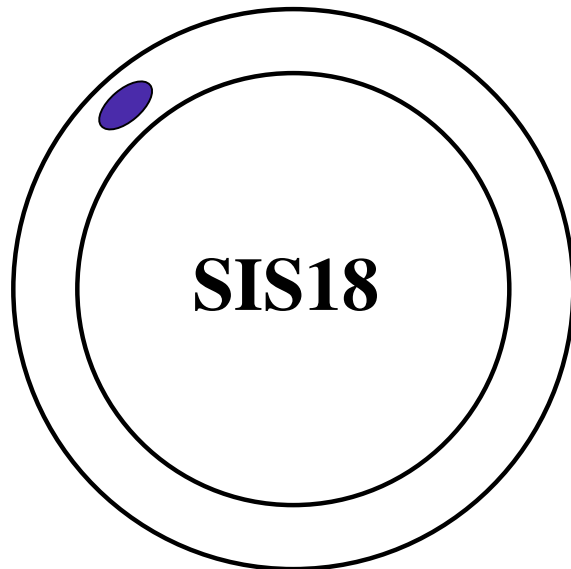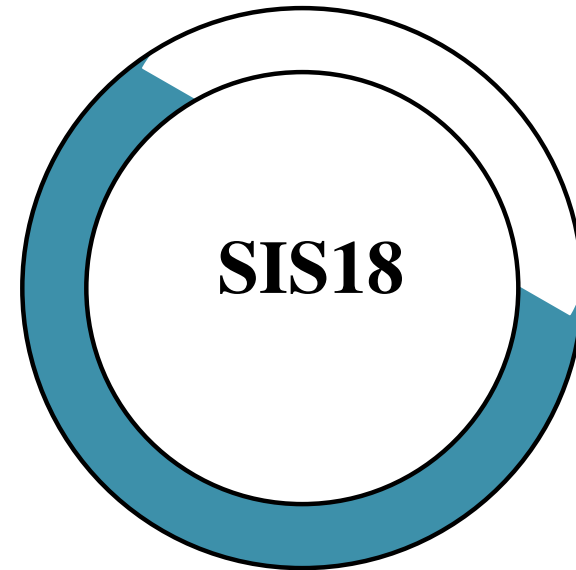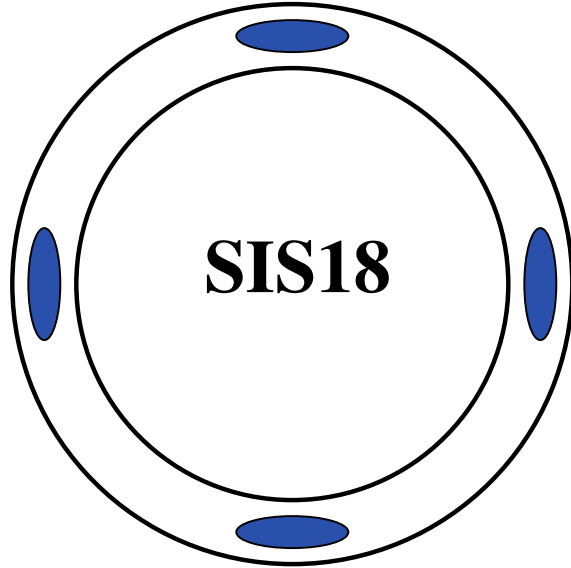
Possible filling patterns for the high current operation of SIS18 (when upgraded as injector of the SIS100):
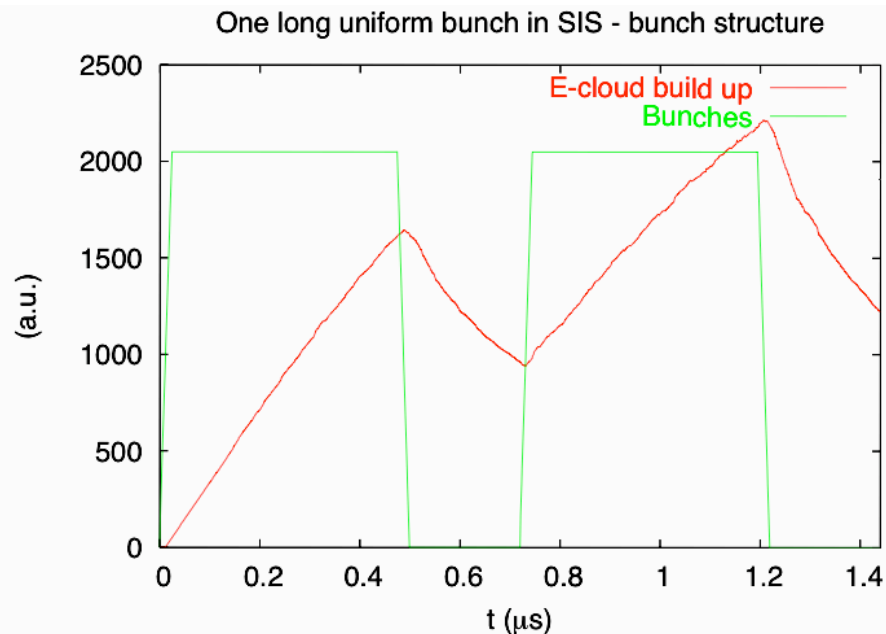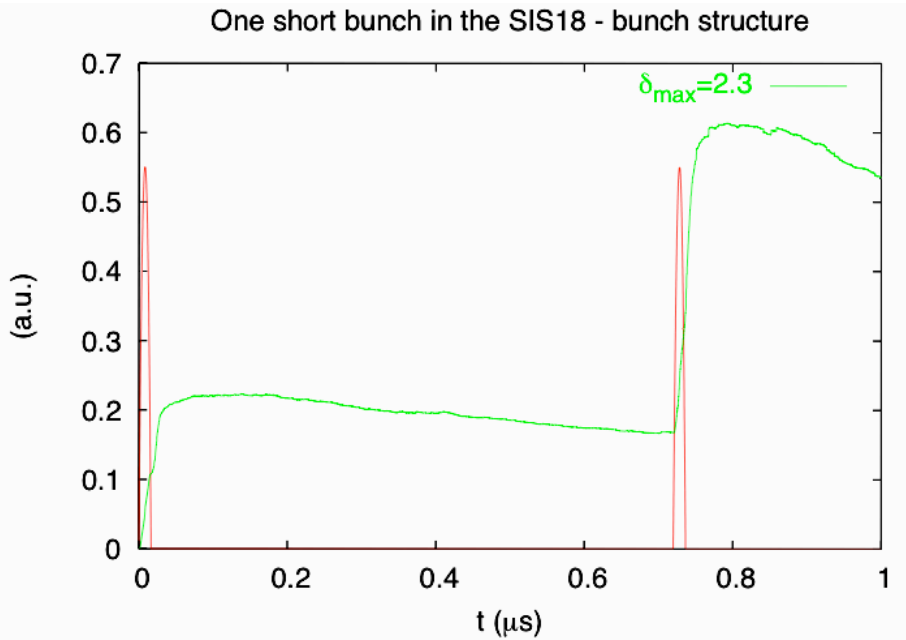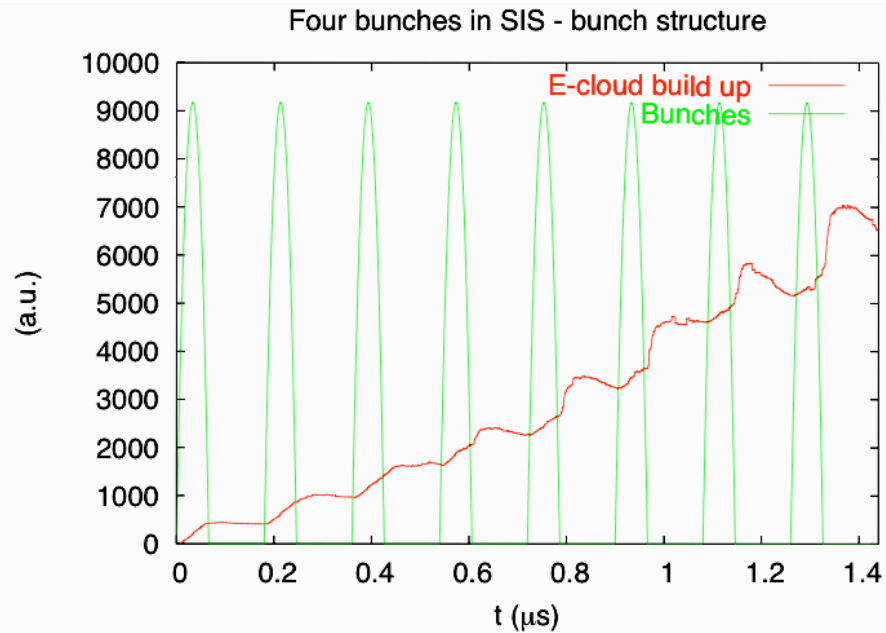
- 4 parabolic bunches (20m)

- 1 long uniform bunch (150m)

- 1 short parabolic bunch (5m)

Table 1: Overview on the SIS18 parameters used in simulations

Circumference	216 m
Bunch population (N_b)	4×10^{10} U^{+73} in the machine
Beam energy	1 GeV/U
Number of bunches	1 or 4
Bunch shape	Parabolic or uniform
Bunch rms-length (σ_z)	5 m, 37.5 m, 1.25 m
Rms-energy spread ($\delta p/p_0$)	1.06×10^{-3}
Mom. compaction (α)	0.0356
Normalized emittances ($\epsilon_{x,yN}$)	6.5/5 μm
Tunes ($Q_{x,y,s}$)	$4.308/3.29/1.4 \times 10^{-3}$
Chromaticities ($\xi_{x,y}$)	corrected or -1
Secondary emission yield	scanned from 1.8 to 2.2
Chamber dimensions $h_{x,y}$	10, 5 cm
Pressure in the beam pipe	0.1 nTorr
Ionization cross section	2 MBarn/U

Results published in „Study of electron cloud formation and instability in the SIS18" (G. Rumolo and O. Boine-Frankenheim) **GSI-Acc-Note-2003-10-001**

Four bunches in SIS - bunch structure

One long uniform bunch in SIS - bunch structure

One short bunch in the SIS18 - bunch structure

Bunch structure and start of the e-cloud build up process for the possible filling patterns of the SIS18 (first 2 turns shown)
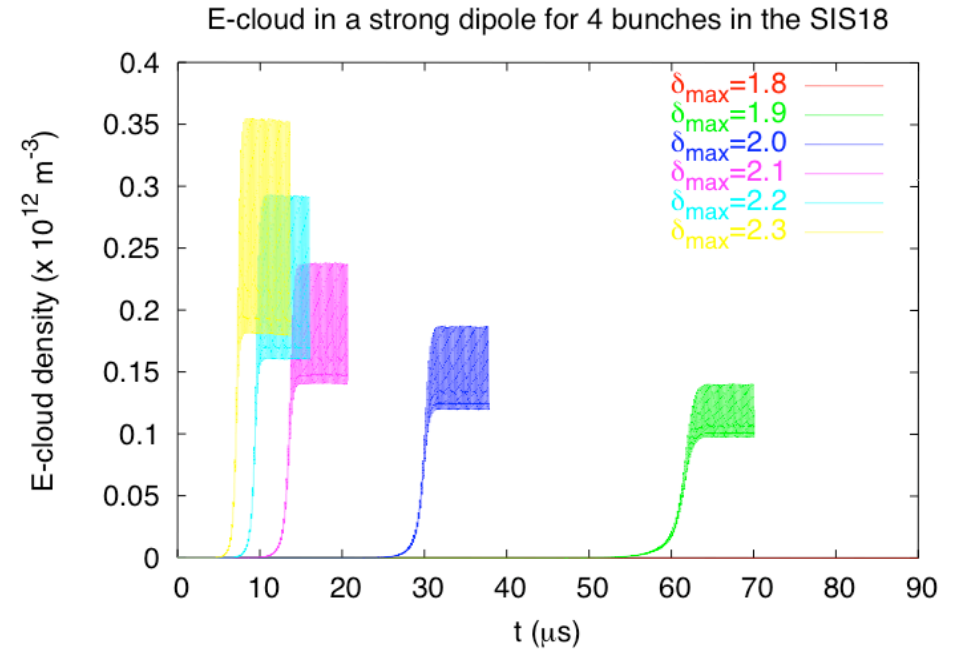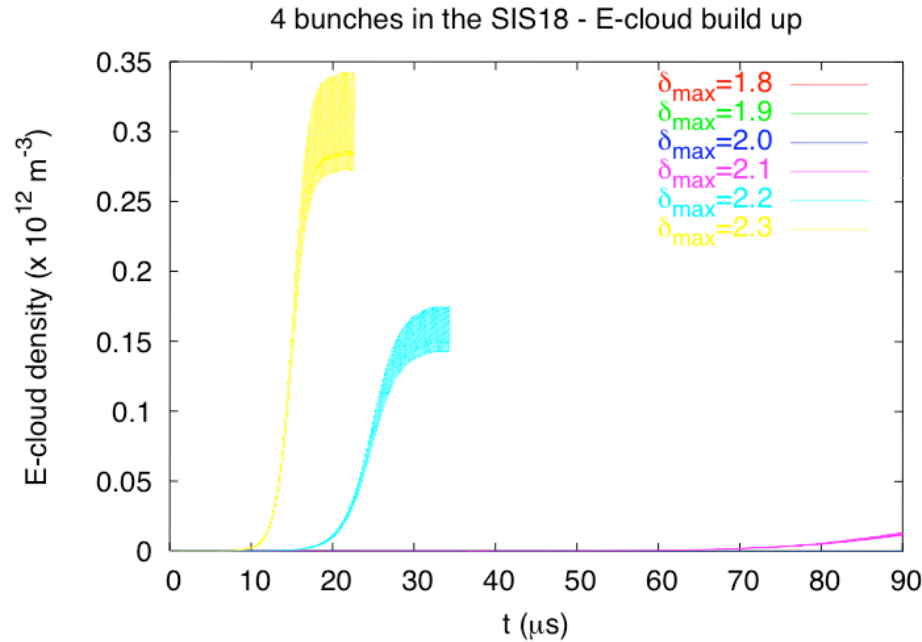
**E-cloud build up** with 4 bunches in a field-free region (left) and in a dipole (right):

- The threshold for the build up is 2.1 in field-free and 1.9 in a dipole
- Saturation values are in the order of 10^{11} e^-/m^3, enough to cause beam instability
- Cimino-Collins parametrization for elastic reflection used.

One long super-bunch - E-cloud build up

One short bunch - Electron cloud build up
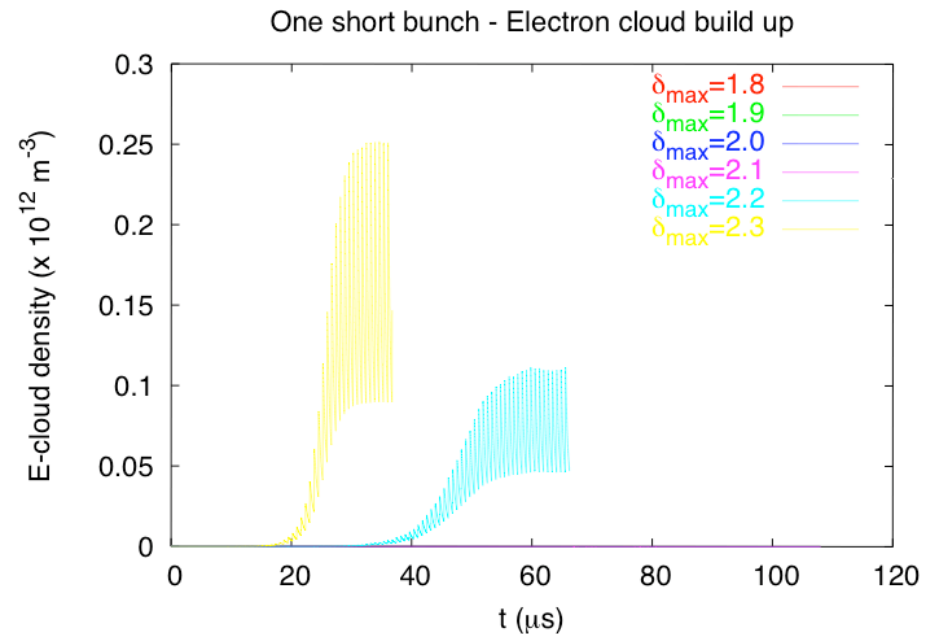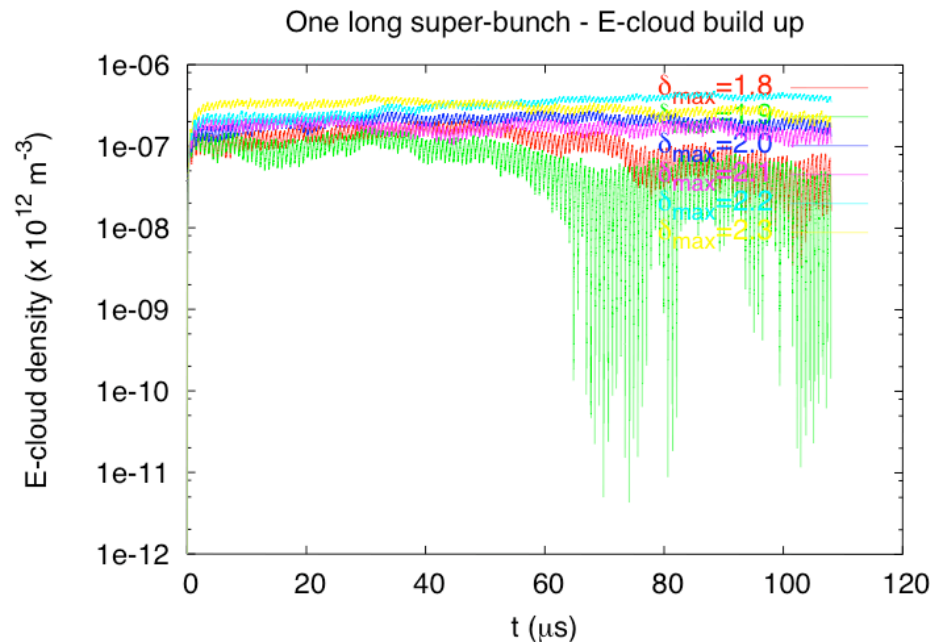
With one single bunch in the machine:

• The super-bunch does **NOT** cause any electron cloud build up even for very high SEY's. The short bunch has a threshold at 2.2

• Saturation values are in the order of 10^{11} e⁻/m³.

It is interesting to show how the recently proposed parametrization for elastically reflected electrons makes a significant difference in the predictions of electron cloud build up.
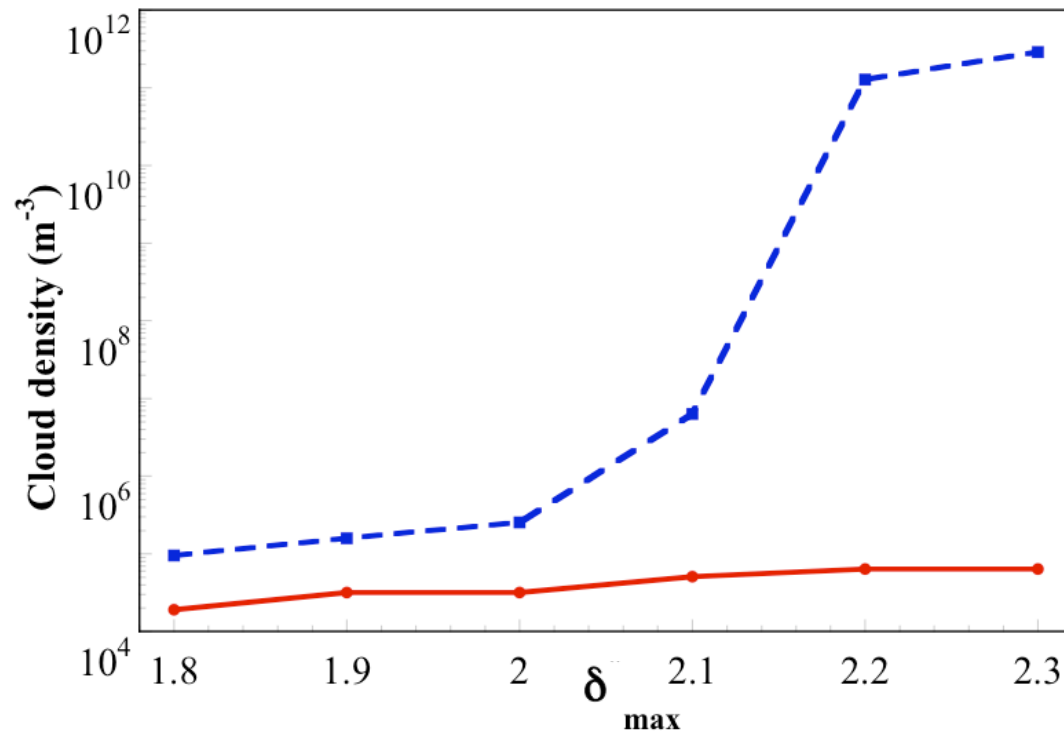
„Can low energy electrons affect high energy physics accelerators ?"

(R. Cimino, I. Collins, M. Furman, F. Ruggiero, G. Rumolo and F. Zimmermann) presently submitted to **Phis. Rev. Letters**

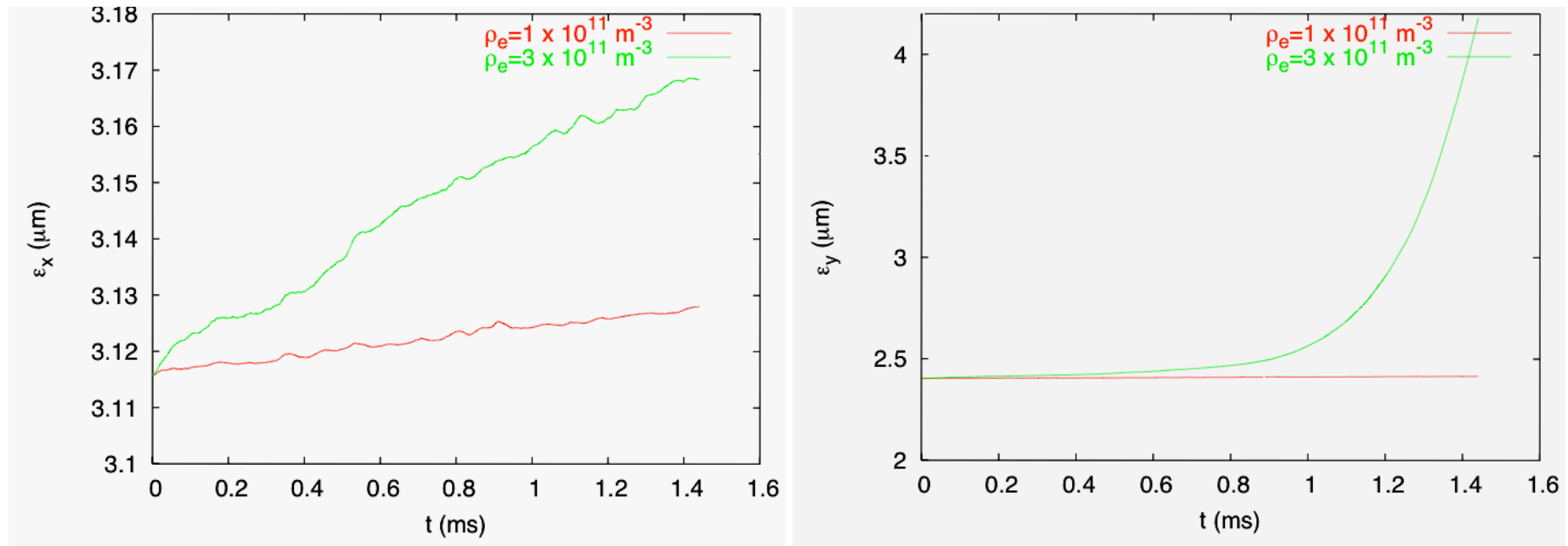# E-cloud instability in SIS18
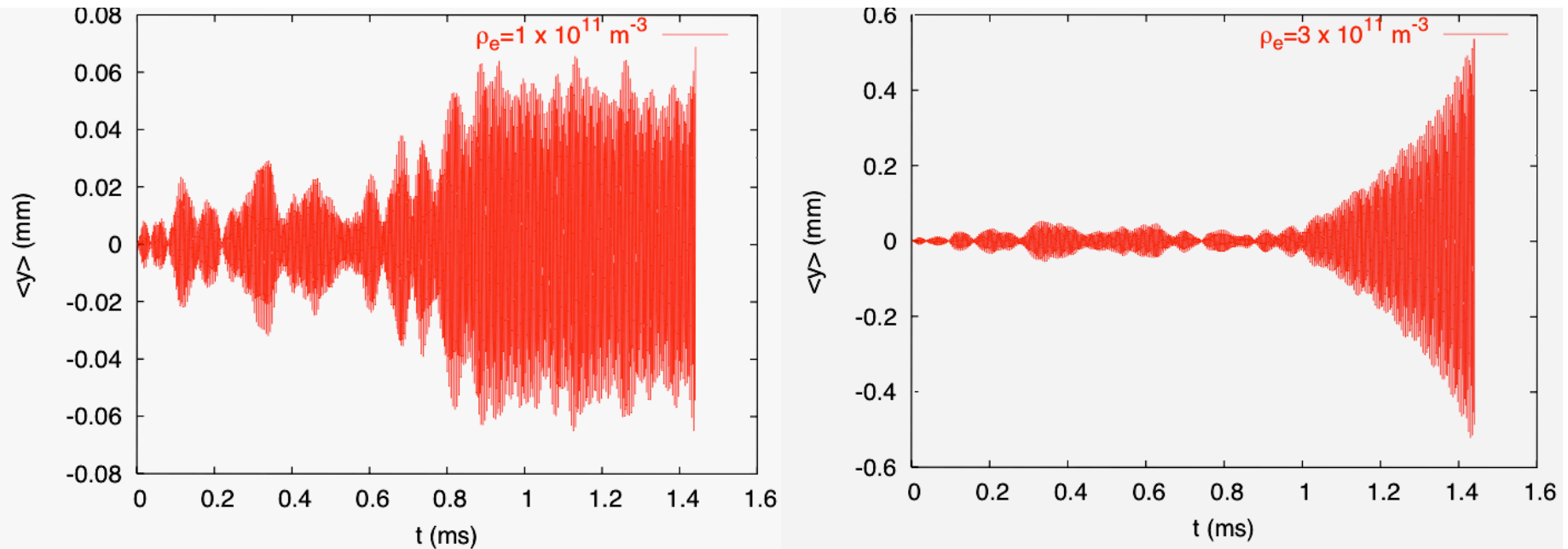
Vertical motion of the bunch centroid for two different values of the e-cloud density

Crossing the threshold for instability:

- An e-cloud density of 10^{11} e$^-$/m^3 is **not** enough to cause a coherent centroid motion

- An e-cloud density of $3 \cdot 10^{11}$ e$^-$/m^3 makes the bunch unstable

E-cloud instability in SIS18 (2)

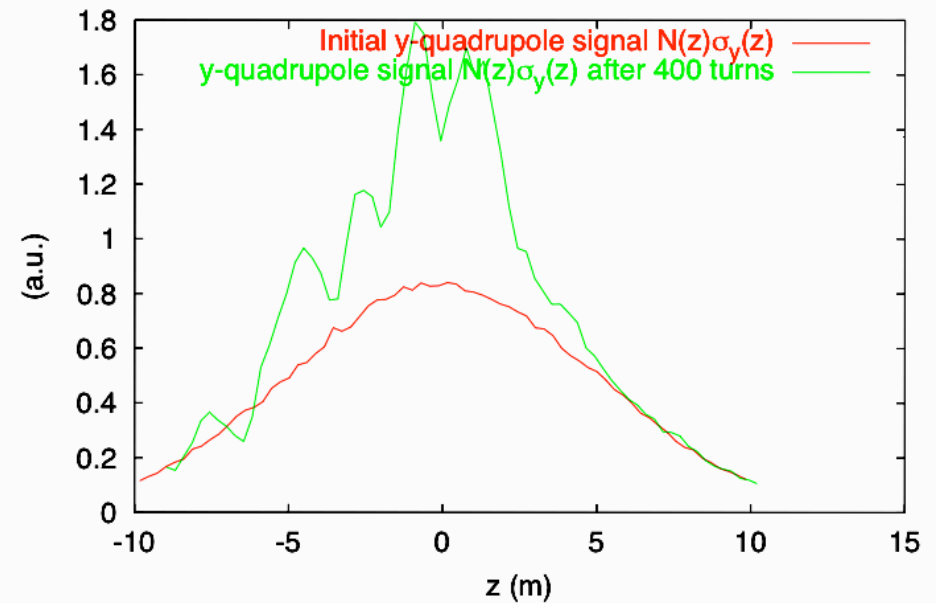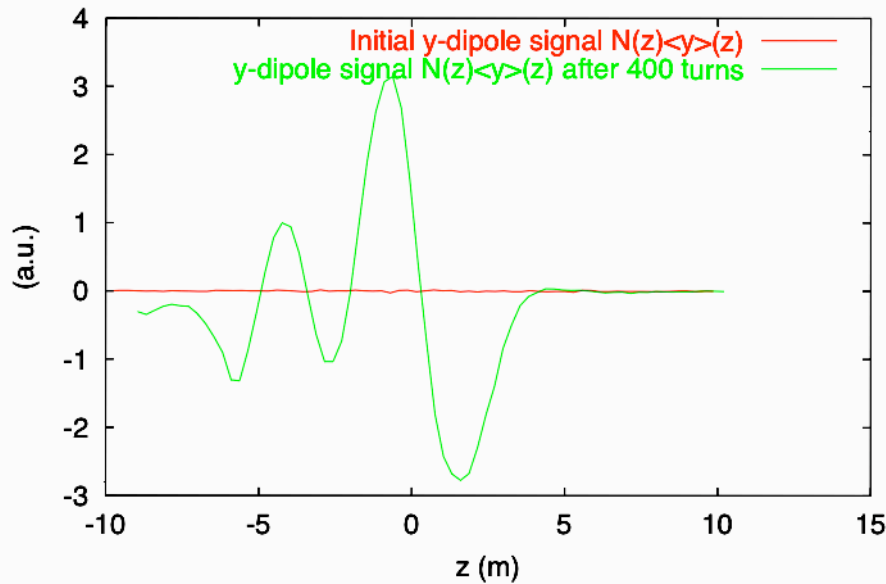Emittance growth for two different values of the e-cloud density

Crossing the threshold for instability:

• E-cloud densities below 3 10^{11} e⁻/m³ only cause incoherent emittance growth

• The coherent instability appears in the vertical plane first.

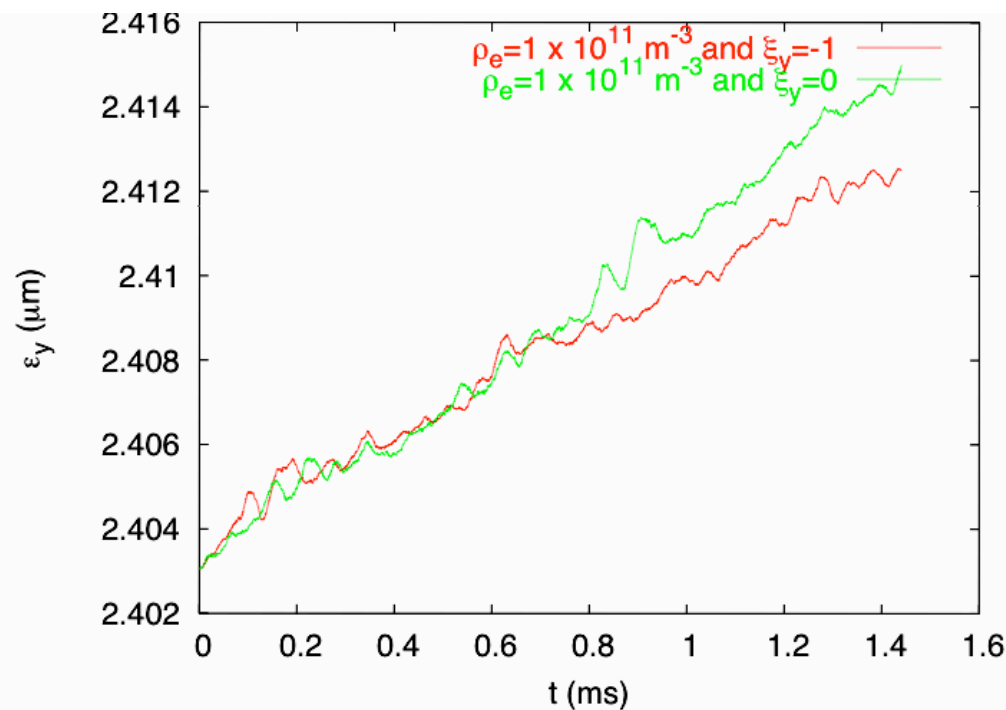# E-cloud instability in SIS18 (3)

Snapshots of dipole and quadrupole signals for an e-cloud density of 3 10^{11} e-/m³

- A coherent unstable oscillation along the bunch has clearly developed after 400 turns

- There is a moderate distributed incoherent rms-size blow-up.

E-cloud instability in SIS18 (4)

Vertical emittance growth for an e-cloud density of 10^{11} e⁻/m^3 and natural or corrected chromaticity

• The effect of chromaticity on the unstable bunch dynamics seems to be negligible !!

Two empty buckets
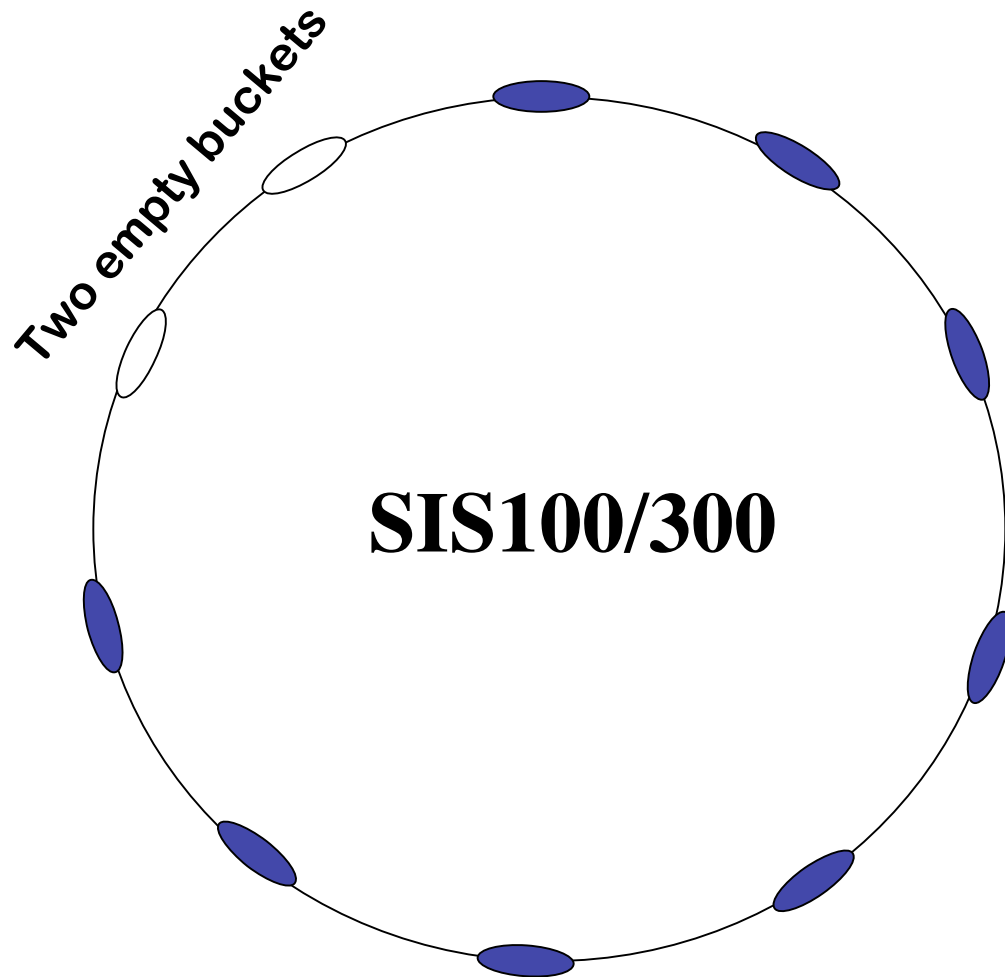
SIS100/300

C=1080 m

E=2.7 GeV/u

10^{12} U^{28+} ions in the machine

The filling pattern in the SIS100/300 consists in 8 bunches followed by 2 empty buckets.

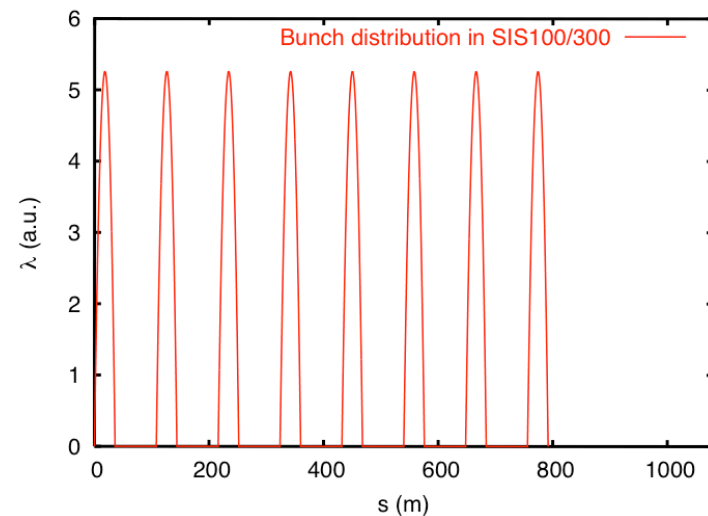Each bunch stretches over about one third of the full bucket.

Bunch distribution in SIS100/300

λ (a.u.)

s (m)

Table 1: Overview on the SIS100/300 parameters used in simulations

|	
Circumference	1080 m
Bunch population (N_b)	10^{12} U^{+28} in the machine
Beam energy	100 MeV to 2.7 GeV/U
Number of bunches	8
Harmonic number	10
Bunch shape	Parabolic
Bunch rms-length (σ_z)	$\approx$9 m
Beam transverse sizes ($\sigma_{x,y}$)	1.0/1.0 cm
Secondary emission yield	scanned from 1.8 to 2.2
Chamber dimensions $h_{x,y}$	scanned from 6 to 12 cm
Pressure in the beam pipe	3.8×10^{-3} nTorr
Ionization cross section	2 MBarn/U

Parametric study for SIS100/300:

- Different shapes and sizes of the beam chamber
- Different values of maximum SEY (δ_{max})
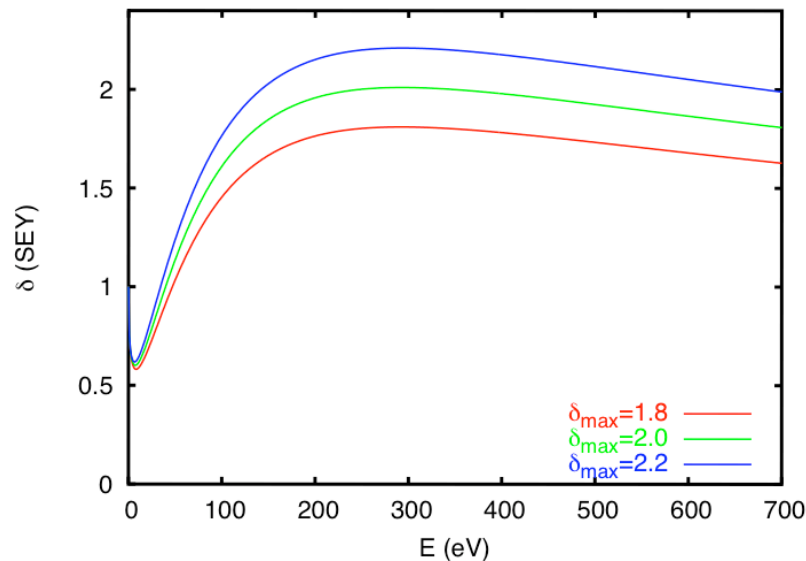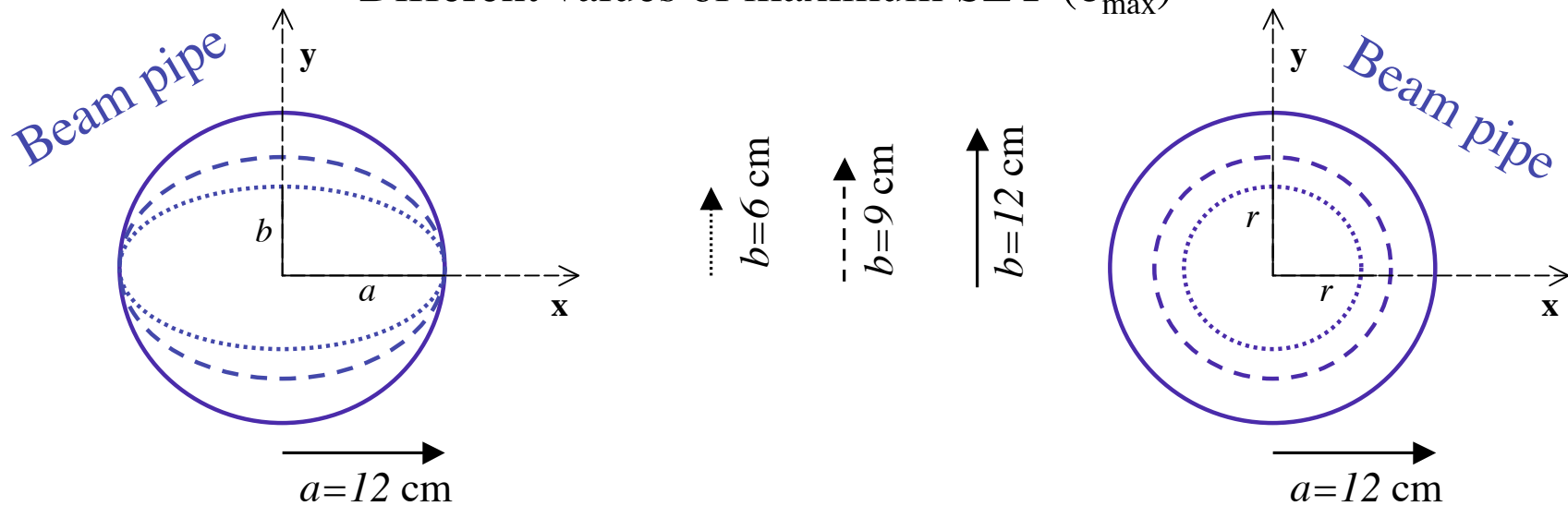
The *Cimino-Collins parametrization* for elastic scattering has always been used in the simulations (probability of reflection approaching 1 in the very low energy range)
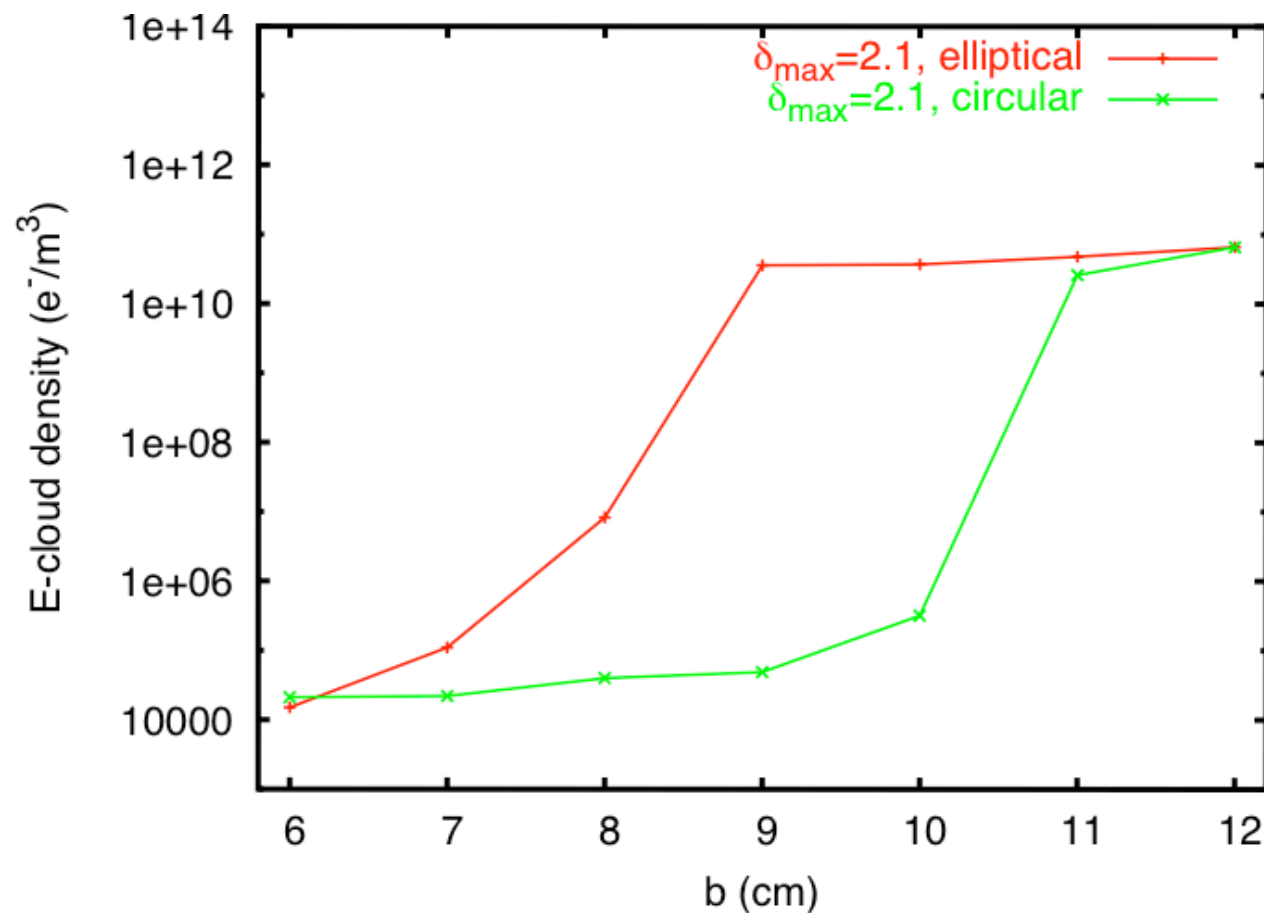
Primary electrons only coming from residual gas ionization
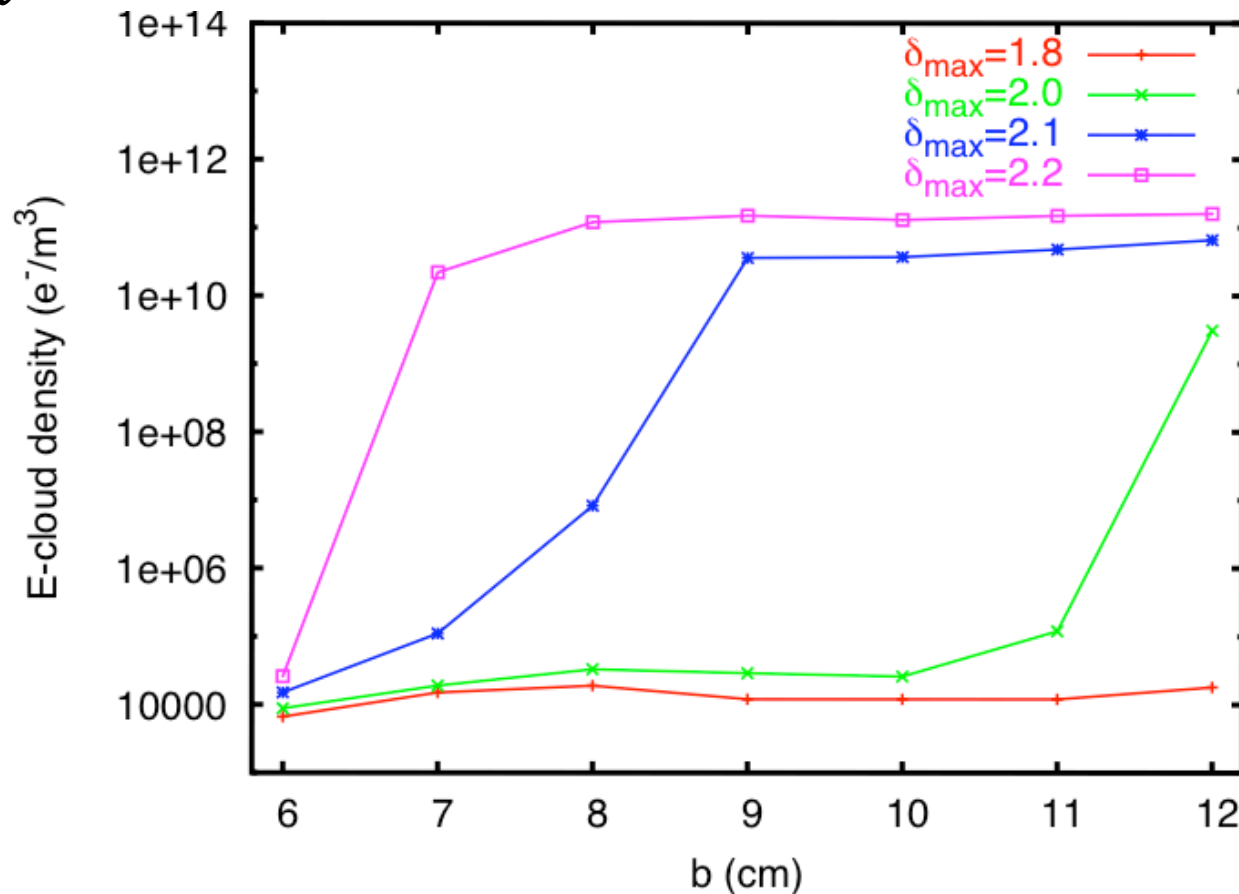
E-cloud density values at saturation for different chamber vertical sizes and different maximum SEY's.

• Flat chambers inhibit cloud formation even for high δ_{max}'s

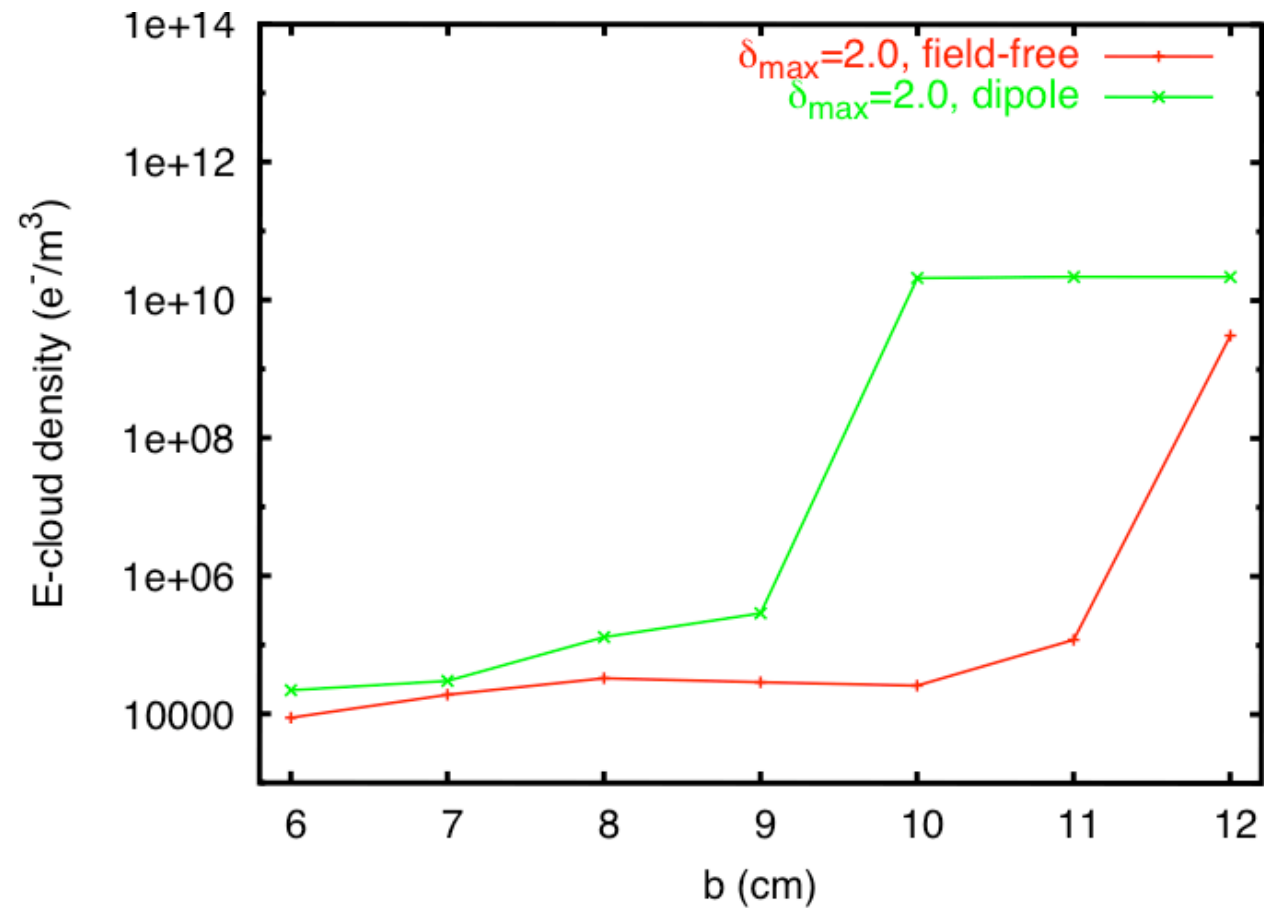• δ_{max}'s up to 1.8 seem to be relatively safe

Primary electrons only coming from residual gas ionization

E-cloud density values at saturation for different chamber shapes and sizes (maximum SEY fixed to 2.1).

In the elliptical case, the horizontal chamber size was fixed to 12cm, whereas the vertical size b was scanned through different values. In the circular case, the radius was changed.
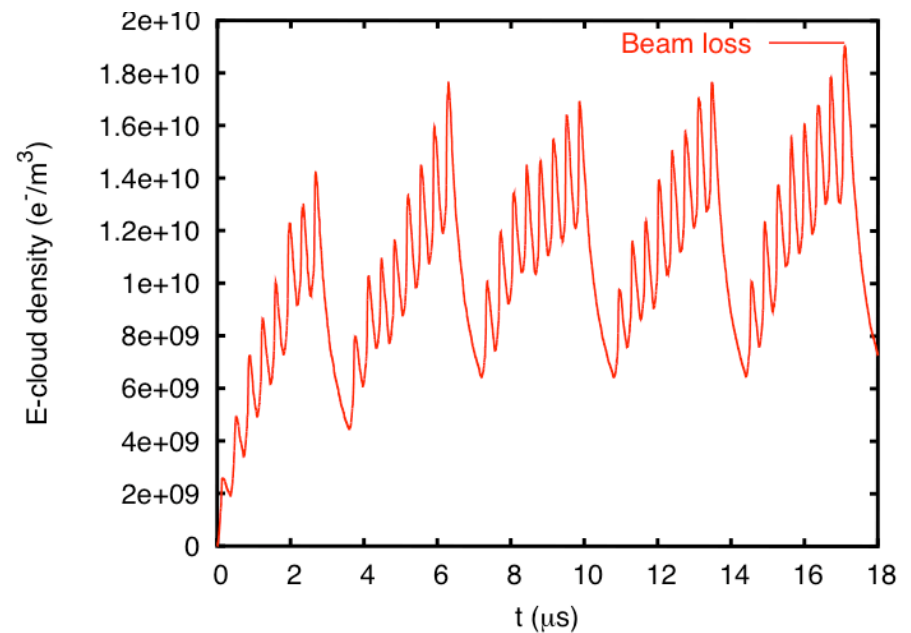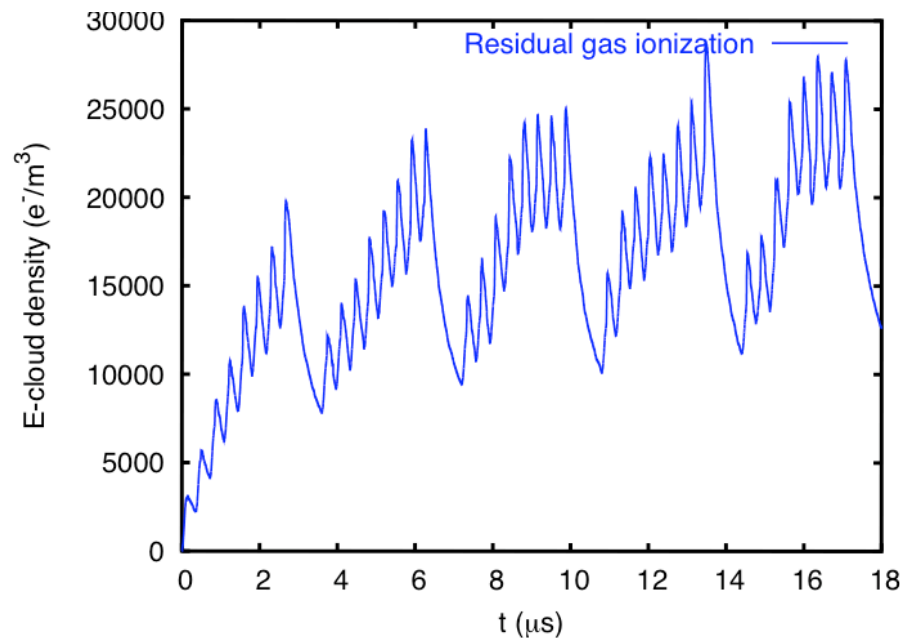
Primary electrons only coming from residual gas ionization

E-cloud density values at saturation for different chamber vertical sizes and in field-free or dipole regions (maximum SEY fixed to 2.0).
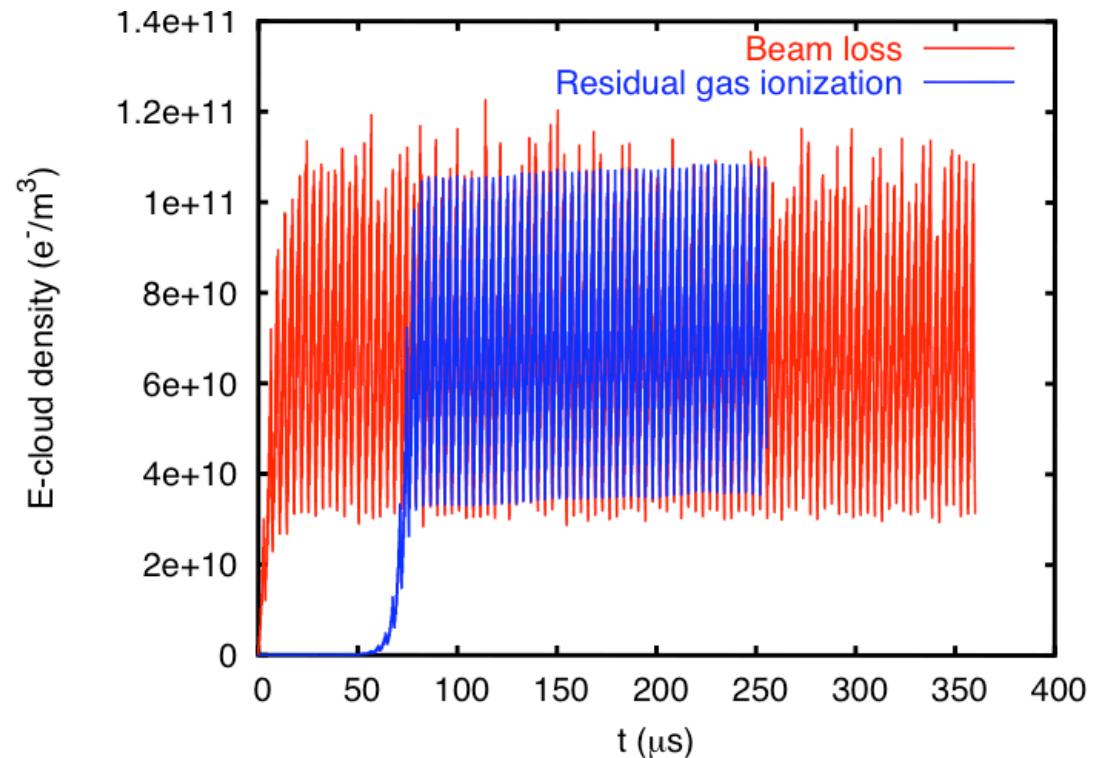
• The threshold for e-cloud formation is lower in a dipole

*Primary electrons from residual gas ionization
or beam loss*

E-cloud evolutions (5 turns) in the SIS100 as expected from gas ionization or beam losses

The e-cloud build up is qualitatively the same whichever is the initial seed (maximum SEY fixed to 2.0), yet the number of electrons in the vacuum chamber reaches **much higher values from beam losses** because of the much higher production rate !

Primary electrons from residual gas ionization or beam loss

E-cloud evolutions in the SIS100 as expected from gas ionization or beam losses

The e-cloud density saturates at the same level if electrons multipact due to secondary emission (maximum SEY fixed to 2.1 and beam radius to 12cm). In this case the mechanism of primary production does **NOT** determine the number of electrons inside the beam pipe.

Primary electrons from residual gas ionization or beam loss
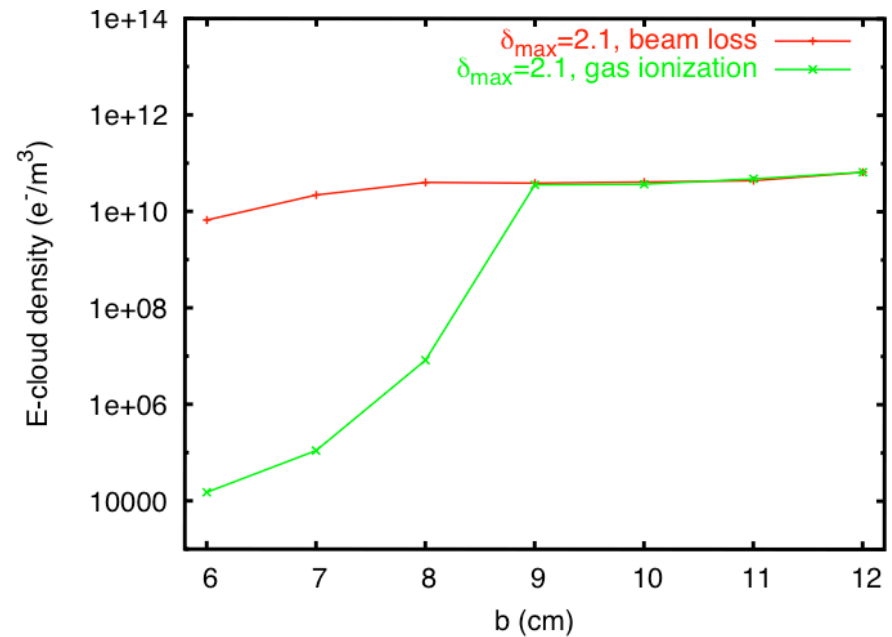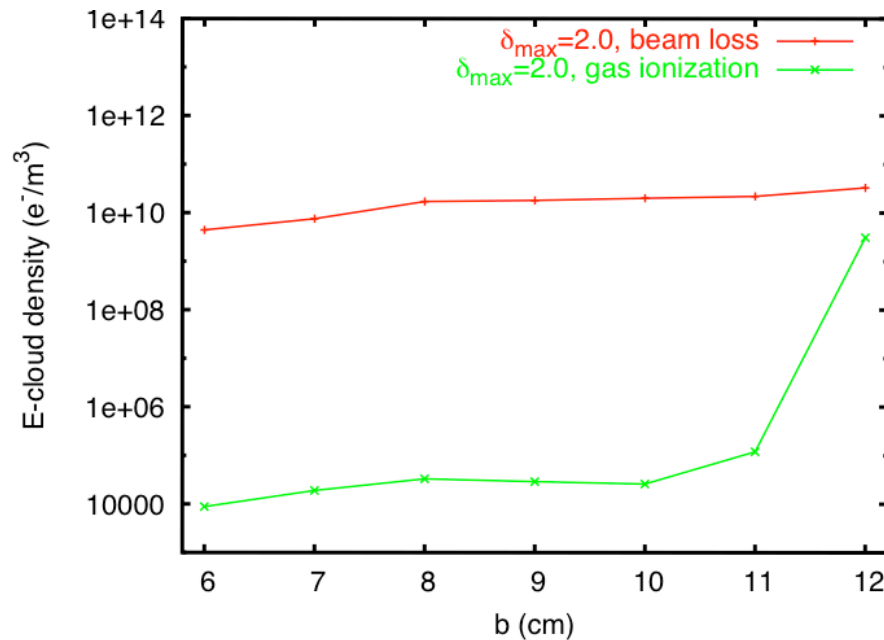
E-cloud density values at saturation for different chamber vertical sizes and different seed electrons (maximum SEY fixed to 2.0 or 2.1).

- Ion losses may cause high electron concentrations in the vacuum chamber

- Saturation values are comparable only when the gas electrons multiply.

Summarizing: can the electron cloud harm the performance of GSI machines ?

- SIS18 could suffer from electron cloud when upgraded to become an injector for SIS100.

- The threshold for e-cloud formation is rather high ($\delta_{max} \sim 2.1$), thus it can be relatively easy to have an inner pipe wall with a SEY below this value. Some scrubbing could be necessary.

- In the SIS100/300, too, the threshold for e-cloud formation is quite high, especially for smaller chamber radii.

- Due to beam loss, there might be accumulation of electrons up to relatively high densities.

- Both in SIS18 and SIS100/300 thresholds are lower in dipoles.

Some open questions...

- Existing electron cloud simulation codes have been benchmarked against each other

  http://www.slap.cern.ch/collective/ecloud02/ecsim/index.html

  Differences in modeling can still lead to significantly different results

- Build up codes have also been benchmarked against measurements: the qualitative agreement is very good, though it has not been confirmed to date by a reliable quantitative agreement.

- The power of prediction of the codes has proved good (SPS, KEKB). However, why have ISIS and DAΦNE not observed any electron cloud yet ?

Ongoing work

- Debugging and upgrading of the codes to make them able to handle different situations (short or long bunches, low or high energy, etc.). Large interlab teams constantly working on the development.

- Experimental program to improve the knowledge of the necessary laboratory inputs for the simulation codes.

- **Coasting beams ?** Build up and interaction with the beam are in this case intimately interconnected and need to be modeled within the same simulation tool.

- Detailed simulation of the coupled bunch instability

- Analytical approach to model electron cloud phenomena

Acknowledgements

All those who have actively contributed to this work....

Electron cloud issues and progress will be discussed and summarized in the forthcoming workshop **ECLOUD'04** (18-23 April 2004, Napa CA)

http://icfa-ecloud04.web.cern.ch/icfa-ecloud04/

31st ICFA Advanced Beam Dynamics Workshop on
Electron-Cloud Effects "ECLOUD04"
Napa (California), April 19-22, 2004
Sponsored by LBNL, CERN, ORNL and SNS

www.waterpear.com

http://www.cern.ch/icfa-ecloud04
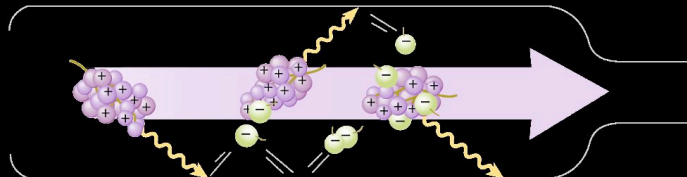
This ICFA workshop will review experimental methods and results obtained within the past few years on the electron-cloud effect (ECE), along with progress on its understanding obtained from simulations and analytic theory, and the effectiveness of mitigation mechanisms. As in previous workshops dealing with the ECE (KEK, July 1997; Santa Fe, February 2000; KEK, September 2001; CERN, April 2002), the focus of ECLOUD04 will be broad, covering all aspects of the phenomenon.

The workshop will take place in the Napa Embassy Suites (http://www.embassynapa.com/), which will also be the official conference hotel. The deadline for abstract submission is January 30, 2004. The deadline for hotel reservations is March 18, 2004. Electronic proceedings will be published, and authors will be encouraged to submit their contributions to a special edition of PRST-AB (details on abstract submission, registration, hotel reservations and transportation will be mailed out and posted on the ECLOUD04 website).

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The end

Code benchmarking

- e- cloud induced desorption main source of gas density ➜ need of benchmarking of code ecloud (G. Rumolo, F. Zimmermann) to use it for predictive-quantitative estimations

- Benchmark against SPS pick-up measurements (M. Jimenez et al.)

- Primary source of electrons : gas ionisation

  – 72 bunches,
  – $8.3 \cdot 10^{10}$ protons/bunch,
  – 30 cm, 26 GeV bunches
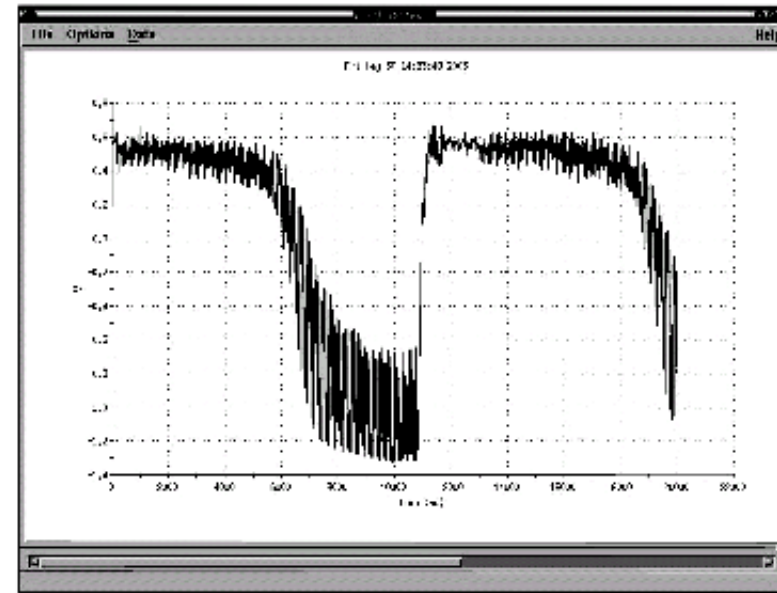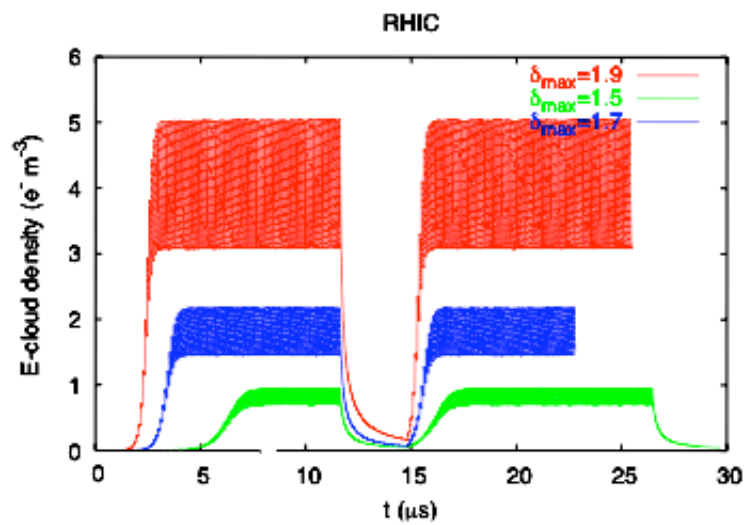 – Field free region
  – SPS-MBA geometry (r_H 76 mm r_V 17.5 mm)
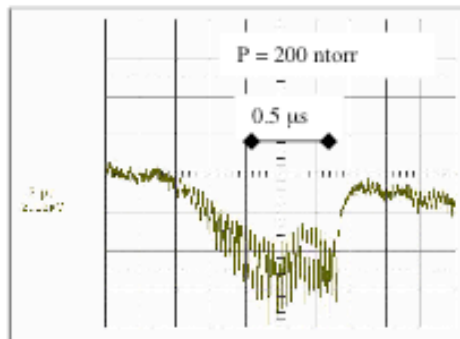
Courtesy of M. Jimenez
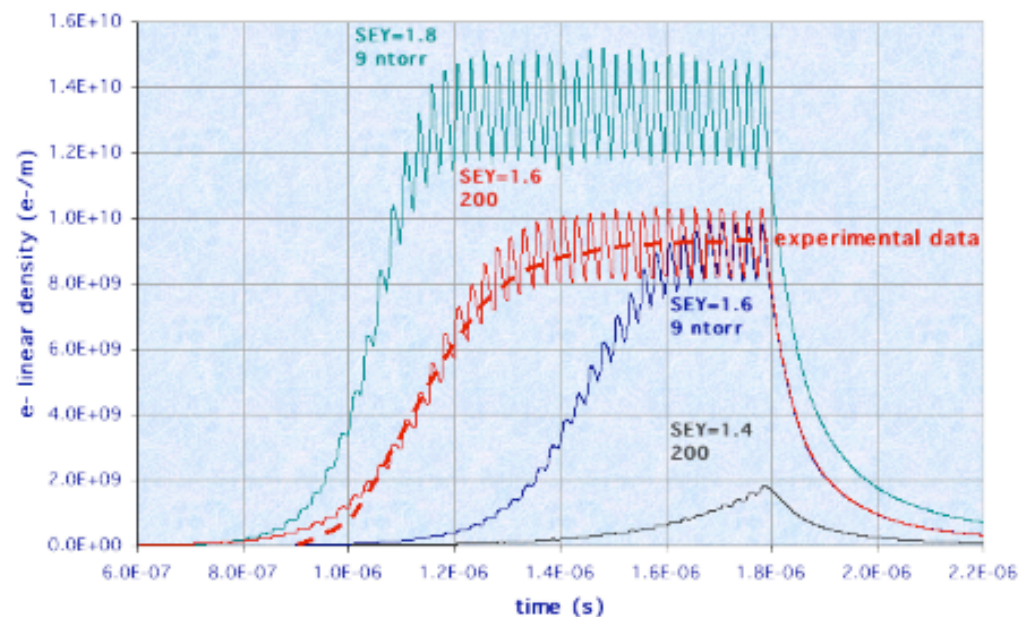
Adriana Rossi CERN LHC/VAC

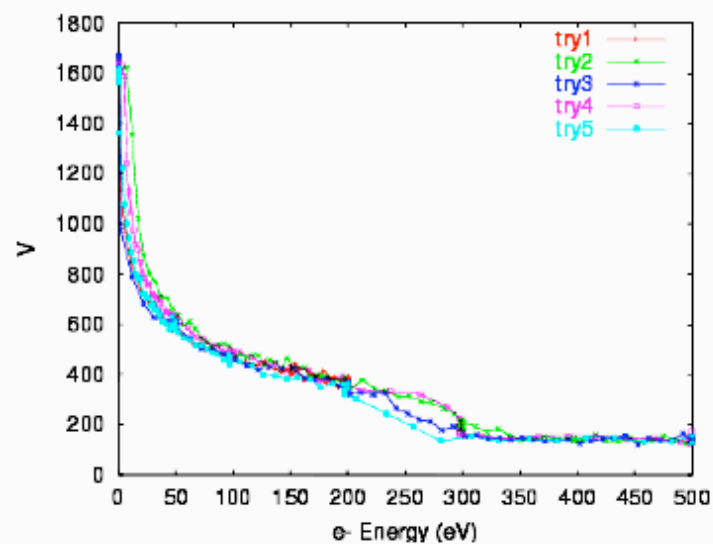Picture from a dedicated electron detector installed in a field−free region in RHIC
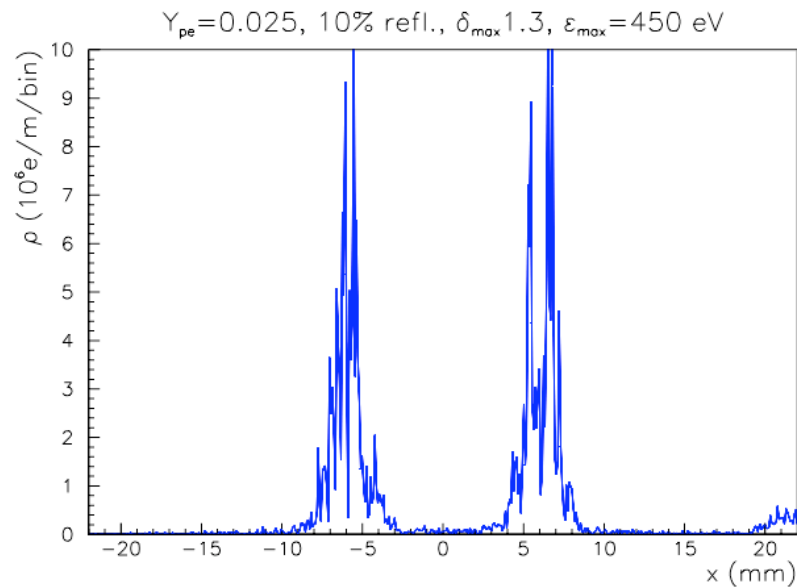
Simulations carried out with the ECLOUD code for different values of the SEY_max.

*** Electron Cloud simulations & experiment, energy spectrum in RHIC**
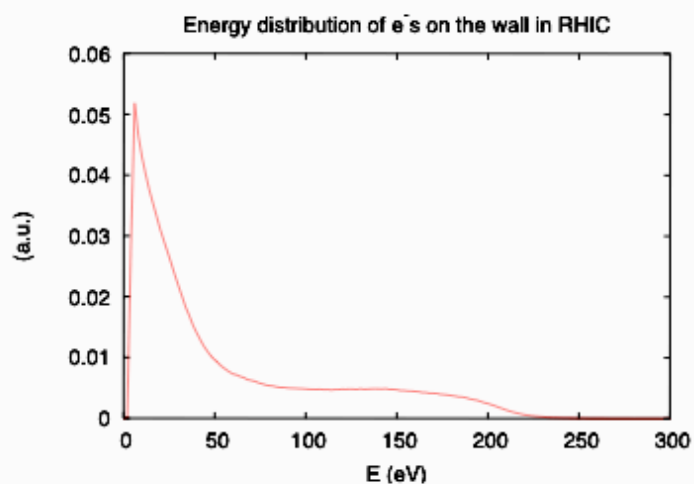
Picture from the electron energy analyser installed in a field–free region in RHIC

Simulations carried out with the ECLOUD code.

Y$_{pe}$=0.025, 10% refl., δ_{max}1.3, ε_{max}=450 eV

**Simulated e-cloud density** in an LHC dipole (projected horizontal charge density)

Measured horizontal distribution of the electron cloud at the SPS for a bunch intensity of 8.6 10^{10} p/b (almost nominal intensity for LHC) and a magnetic field of 10^{-2} T.
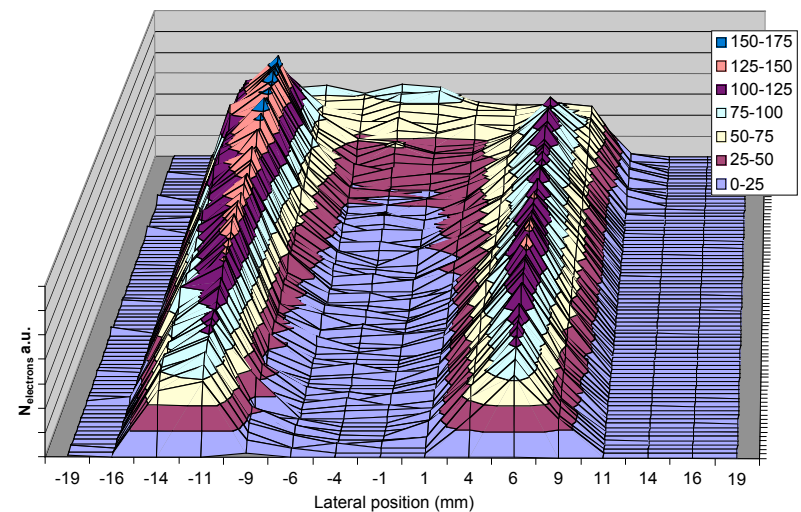
Back to the open questions

Re-diffused electrons can significantly change the spectra of the re-emitted electrons, and therefore affect the full build up simulation results !!

Spectra of re-emitted electrons
with the re-diffused component
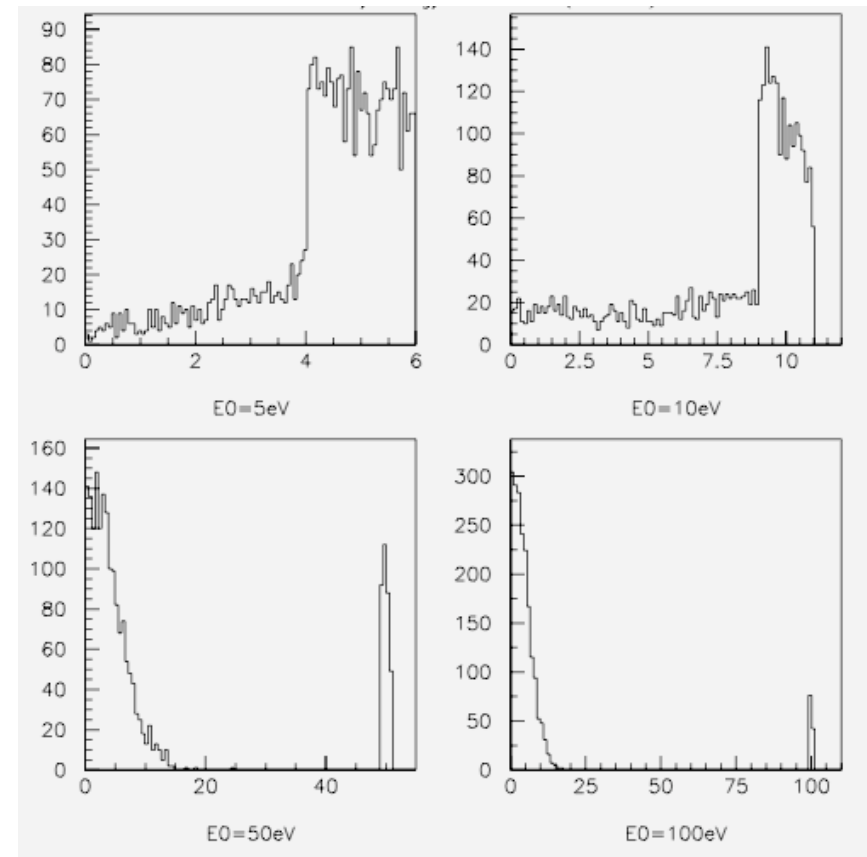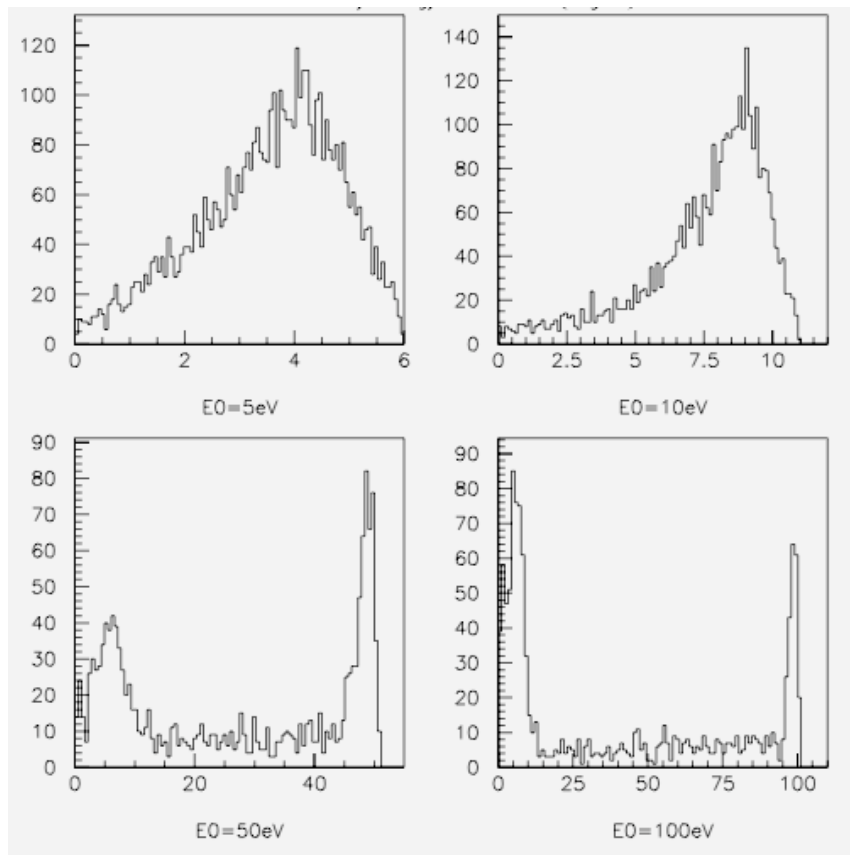
Spectra of re-emitted electrons
without the re-diffused component